Evapotranspiration and energy flux differences between a forest and a grassland site in the subalpine zone in the Bernese Oberland

Unterschiede der Verdunstung und Energiebilanz eines Waldes und eines Graslands in der subalpinen Zone im Berner Oberland

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Abstract

Economic pressure on farmers in mountainous areas of Switzerland has led to considerable abandonment of traditionally used lands. Such abandonments of grasslands, that is primarily pasture and hay meadows, typically leads to invasion of shrubs and later forests, the potential climax vegetation in the subalpine zone of the Swiss Alps. Because dark forests absorb a considerably higher share of the solar radiation energy than what is received at the earth’s surface by brighter colored grasslands, this potentially leads to a climate feedback mechanism that enhances local climate change in addition to global warming related to the increase in greenhouse gas concentrations since pre-industrial times. In our study we aimed at quantifying the order of magnitude of this feedback mechanism related to land use change from grassland to forest, which is typical of the higher elevations in the Alps based on summer season measurements of the surface energy budget and evapotranspiration in the Leissigen research catchment in the Bernese Oberland.

1 Introduction

The climate of the earth is driven by the net radiation available at its surface to drive ground heat flux, sensible heat flux, and evapotranspiration (Le Treut et al. 2007, p. 96). Vegetation plays a key role for local and regional climates, since the transpiration of the green biomass that is closely linked with photosynthetic assimilation consumes a considerable share of available energy (Bonan 2004). Global circulation models (GCMs) that are used to simulate past, current and future climates, have been improved substantially, and some of the newest generation GCMs include vegetation–climate feedback processes in sufficient detail to investigate the role
of vegetation in the global climate system (see e.g. Meehl et al. 2007, p. 789ff). Since earlier
generations of GCMs used relatively coarse spatial resolutions in their computations, the
assessment of climate change scenarios has largely been a top-down approach (climate impact
studies). The finer spatial resolution of the newest GCMs, in combination with the still
increasing computational power of super computers, allows now more and more to investigate
climate feedback processes from a bottom-up approach (see Denman et al. 2007, p. 521–576
for a more detailed overview over different top-down and bottom-up approaches in climate
change research). At the same time, the role of human induced land-use changes and their
feedback to climate has become of broad scientific interest (see e.g. DeFries et al. 2004).

Several regional-scale modeling exercises have shown how important vegetation feedbacks are
for local and regional climates (e.g. Chapin et al. 2000; Schneider et al. 2004; Pielke 2005;
Schneider and Eugster 2005; Schneider and Eugster 2007; Meehl et al. 2007, p. 789ff).
Conceptually, it appears clear that if vegetation with a large leaf surface area is replaced by
another vegetation with less biomass, then the transpiration and thus evapotranspiration tends
to decrease. This is expected if for example tropical forest is replaced by seasonal crops or
pasture (e.g. Lawton et al. 2001). On the other hand, in extratropical climates the net effect of
replacing a certain vegetation with another functional type may be less obvious. Agricultural
crops that are well fertilized can easily yield the same productivity as a forest, or even more,
and thus the climatic effect of land use changes may differ considerably among biomes.

Recent studies from the northern latitudes have shown that evapotranspiration rates from
coniferous forests growing on upland soils in the boreal zone are well below potential
evapotranspiration (Baldocchi et al. 2000). Thus, they exhibit a strong control over the regional
surface energy budget (Kelliher et al. 1993, Eugster et al. 2000). This biophysical control of
boreal forests over the regional scale evapotranspiration has only been incorporated in
European and US weather forecasting models during the last decade (Betts et al. 1998). Prior
to this modification, regional evapotranspiration and precipitation rates in the boreal forest were
significantly overestimated for the months of June and July (Betts et al. 1998).

Similar data from comparable forest types in the Alps did not exist so far, or at best did not
directly compare forests with grassland under otherwise similar conditions. Typically,
evapotranspiration was rather estimated than measured in older studies, and the general
understanding that forests transpire more water than grasslands or heath (Lerch 1991, p. 127;
Franz 1979, p. 123) was mostly not quantified in sufficient detail that would allow to use that
information for the validation of numerical models, be it GCMs or one-dimensional process
models that try to simulate feedback processes between the vegetated land surface and climate.

In German speeking Europe, the approach used by Walter and Lieth (1967) to estimate
potential evapotranspiration is still widely used. They estimated potential evapotranspiration on
a monthly basis to be roughly the monthly mean temperature in °C above freezing (0°C),
multiplied by a factor 2 to yield mm per month. Since experience showed that this relationship
was not perfectly linear in semi-arid and arid climates, the climate diagrams after Walter and
Lieth (1967) also show a second curve where a factor 3 is used to estimate potential
evapotranspiration. In the French territories, the approach suggested by Turc (1961) was widely
used and is still an important means for estimating potential evapotranspiration from
agricultural crops based on generally available monthly climate data. In the U.S.A. the
approach by Thornthwaite (1948) is more commonly used than Walter and Lieth (1967), but is
based on a similarly simple concept. As the need for better temporal resolution than monthly or
weekly means was required, the Penman-Monteith approach (the hydrological evaporation
concept proposed by Penman 1948 was extended by Monteith 1965 to also include vegetation
controls over the transpiration process) became popular, since it even allows to model diurnal
cycles of evapotranspiration. Despite their usefulness in many applications all these approaches
have a short-coming for modern climate change studies in that they rather predict potential than
actual transpiration, and that they are models, not actual measurements. As the most recent
IPCC report (Solomon et al. 2007) states, there are still very limited direct measurements of
actual evapotranspiration over global land areas (Trenberth et al. 2007, p. 260).

Our goal in this paired-sites study was thus to obtain measurements of evapotranspiration,
sensible heat flux, ground heat flux, and net radiation for two contrasting ecosystems in the
Swiss pre-Alps (Fig. 1). We aimed at quantifying the difference in energy fluxes measured over
subalpine Norway spruce (Picea abies (L.) H. Karsten) forest and over grassland during the
peak growing season.

2 Material and Methods

2.1 Sites

Two sites, one an extensively used subalpine grassland, the other a nearby young (approx.
15-yr) Norway spruce forest stand (Picea abies (L.) Karst.), were selected on a North-facing
slope in the Spissibach Natural Hazards research catchment (Figure 2) near Thun (Switzerland)
at similar altitudes of 1393 and 1280 m above sea level, respectively. Local soils are moist
regosols (Hurni 2004) that are partially containing carbonate. At some localities, gley brown
earth dominates. High stone content and low water retention capacity characterize the soils
(Hurni 2004).

Micrometeorological sensors were installed on a 10-meter tower over grassland at 0.5 and 2.6
m above ground (Figure 3). Over forest, the instruments were mounted on a hanging 2-m tower
that was suspended below a stainless steel wire at a height of roughly 5 m above the canopy of
the spruce stand (Figure 4). Measurements above the forest floor were performed with similar
instrumentation (Figure 5; see details below). Data collection began on 1 June and ended on 20
October 1999, with all equipment being operational by 8 July. The climatic temperature lapse
rate to correct our own measurements for the 113 m elevational difference between the two
sites was determined from routine weather data measured at Interlaken (580 m a.s.l.) and
Jungfraujoch (3580 m a.s.l.) which are available from the MeteoSwiss digital database. Both
our sites are located within 18.5 km from these two MeteoSwiss long-term weather stations so
that the temperature gradient determined in that way should be representative for our research
catchment.
2.2 Flux measurements

The energy budget of a surface can be expressed by the equation

\[ R_n = H + LE + G, \]  

where \( R_n \) is net radiation (short-wave and long-wave components), \( H \) is sensible heat flux, \( LE \) is latent heat flux or evapotranspiration, and \( G \) is ground heat flux, all measured in units of W m\(^{-2}\).

We use the meteorological convention that radiation fluxes (\( R_n \) and its components) are positive when directed towards the Earth’s surface, whereas the resulting energy fluxes (\( H \), \( LE \), and \( G \)) are taken positive when directed away from the surface.

Net radiation (\( R_n \)) was measured at each site with Swissteco (Oberriet, Switzerland) net pyrradiometers that were aspirated with dried air to prevent condensation on the optical domes and overheating of the thermal sensors (Eugster et al. 1997). A low power consumption aquarium pump was used to pump ambient air through a desiccant (silica gel) to eliminate moisture (see Figure 4 for example). The outlet was connected with the inside volume of the lupolene domes of the net radiometers to keep them inflated (lupolene is a plastic that is transparent to most of the short-wave and long-wave radiation to be measured by a pyrradiometer). The exhaust was finally guided over the outer surfaces of the two domes to minimize overheating of the lupolene. Ground heat flux (\( G \)) was measured with three (grassland; manufactured by Middleton Instruments, Melbourne, Australia) or four (forest floor; manufactured by Hukseflux, Delft, The Netherlands) heat flux plates inserted horizontally into the soil at a few centimeters depth in the A horizon of the soils. Measurements were corrected for the temporal change in heat content of the soil slab above the heat flux sensors by temperature measurements from one soil thermistor per heat flux plate and from three (grassland) to six (forest floor) time-domain reflectometry soil moisture probes (Campbell Scientific Ltd., Loughborough, U.K.) that provided volumetric soil moisture content. Soil heat capacity was estimated according to Oke (1987) based on the organic and mineral fraction of the soil, and its volumetric water content.

Sensible heat flux (\( H \)) and evapotranspiration (\( LE \)) were measured with the Bowen ratio energy balance (BREB) technique (Bowen 1926, Garratt 1984) using aspirated and calibrated psychrometers at two heights above the canopy or above the forest floor. For the grassland (Figure 3) and forest canopy (Figure 4) we used identical psychrometers that were developed by Prof. Alexander Cernusca, University of Innsbruck, Austria. On the forest floor we used two replicates of a mini-BREB instrument that combines two psychrometers in one housing with one fan to pull the air through both levels (Figure 5). The two inlets are 8 cm apart and in each of the two tubes seen in Figure 5 the dry bulb sensor is 1.5 cm upwind from the wet bulb sensor to avoid interferences between the two sensors. The micro-BREB concept was first used by Ashktorab et al. (1989) in a much less elaborate way to measure soil evaporation between rows of crops using measurements performed on two bags of ambient air sampled above the bare soil between the rows, and a few centimeters above the ground. Although moisture was not measured in the field and questions might arise on how accurate these readings actually were,
the authors obtained reasonable results. This inspired McFadden (1998) to produce special micro-BREB systems together with the first author for his Ph.D. thesis. This concept was then further improved at the University of Bern where the system shown in Figure 5 was produced. Data were accepted if they passed three objective rejection criteria (Ohmura 1982). The effects of phase changes of water vapor were taken into consideration in the computation of daily and monthly averages by correcting sensible heat flux and evapotranspiration for phantom dew if evapotranspiration rates were negative (Gay et al. 1996). This procedure assumes that negative evapotranspiration rates at measurement height during the night correspond to a sensible heat gain at the surface. Evapotranspiration estimates presented here include canopy transpiration, surface evapotranspiration and evapotranspiration of water intercepted by the canopy.

2.3 Estimation of radiation components

We measured net radiation $Rn$ (short-wave and long-wave combined), but not the individual components. However, from $Rn$ and near-surface temperature measurements the four radiative components can be estimated using the relationship

$$Rn = SW_{in} + SW_{refl} + L_{in} + L_{out}$$

where $SW_{in}$ and $SW_{refl}$ denote the short-wave incoming (global) and reflected radiation, and $L_{in}$ and $L_{out}$ the long-wave incoming and emitted (outgoing) radiation, respectively, all in units of $\text{W m}^{-2}$. The sign convention is positive for radiation directed towards the Earth, and negative if directed away from it. $L_{out}$ was estimated from near-surface temperature measurements $T_s$ using Stefan-Boltzmann’s law,

$$L_{out} = T_s^4 \sigma \varepsilon$$

where $\sigma$ is the Stefan Boltzmann constant ($56.703271 \cdot 10^{-9} \text{W m}^{-2} \text{K}^{-4}$) and $\varepsilon$ is the emissivity (dimensionless), which was assumed to be 0.97 for both ecosystem types. $SW_{in}$ and $L_{in}$ were assumed to be the same for both sites given the short horizontal and vertical distance between the sites. Thus, by writing Eq. (1) explicitly for the grassland (G) and the forest (F) site,

$$Rn(G) = SW_{in} + SW_{refl}(G) + L_{in} + L_{out}(G)$$

$$Rn(F) = SW_{in} + SW_{refl}(F) + L_{in} + L_{out}(F)$$

all four radiation components can be computed using an estimated albedo $\alpha$ of 0.19 and 0.085 for grassland and forest, respectively, using the relationship $\alpha = -SW_{refl}/SW_{in}$. In this way, for example,

$$SW_{in} = \frac{Rn(F) - Rn(G) + LW_{out}(F) + LW_{out}(G)}{\alpha(F) - \alpha(G)}$$
2.4 Additional measurements

At the grassland site we measured leaf area index (LAI) with an optical sensor (Li-Cor LAI-2000 Plant Canopy Analyzer; Li-Cor, Lincoln, NE, U.S.A.). This method measures light interception by the canopy and computes LAI using an inverse modeling approach (see Welles and Norman 1990). Due to topographical restrictions we were unable to apply this technique also at the forest site.

3 Results

As expected from the lower albedo of the coniferous forest (McCaughey 1987, Betts and Ball 1997, Deering et al. 1999) the daily average net radiation received at the forest site was greater than that of the grassland site throughout the season (Figure 6b). This is consistent with the 1.1°C higher air temperature observed over the forest canopy (Table 1), which can only partly (0.6°C or 53%) be explained by the difference in altitude between the forest and grassland sites when using the climatic temperature lapse rate between Interlaken and Jungfraujoch as a reference.

The albedo difference between forest and grassland yielded a 115 W m\(^{-2}\) net gain of short-wave radiation by the darker forest canopy as compared to grassland. This albedo effect was partially compensated by larger long-wave radiation losses of 4.8 W m\(^{-2}\) due to the higher surface temperature (temperature effect), resulting in a measured net additional radiative energy gain of 110 W m\(^{-2}\) for the forest as compared to grassland. The forest site thus gained 3.4 times the net energy flux available at the grassland site.

The evapotranspiration rate per unit surface area of forest exceeded that of grassland by a factor of 1.9 (Table 1). Converted to energy units, the difference in evapotranspiration between the two vegetation types consumes 68 W m\(^{-2}\) or roughly 61% of the net radiative energy gained by the combined albedo and temperature effects. Soils at the forest site are kept moister and cooler than at the grassland site (Table 1). Evapotranspiration differences between vegetation types can be explained by the much higher transpiration rates of the forest canopy. Direct evaporation from the forest soil was only of minor importance (Figure 6d) and contributed less than 8% to total forest evapotranspiration as measured above the canopy (Table 1). This ecosystem-scale difference is also confirmed by the consistently higher atmospheric moisture content over the forest canopy as is expressed by the 0.6°C higher wet bulb temperature compared to grassland (Table 1).

Sensible heat flux on average was positive over the forest but negative over the grassland site (Figure 6c). The diurnal cycles at both sites indicate that there is a significant and large heat flux from the atmosphere to the surface during the night (Figures 7b and 8b), although in many cases we had to discard nocturnal values based on three screening criteria (Ohmura 1982). This is in agreement with the concept of nocturnal cold-air drainage flows down-slope along mountain valley slopes (Wagner 1938, Defant 1949, Whiteman 1982, Doran et al. 1990). Since the atmosphere is stably stratified during dark periods, that is, the warmer air is on top of cold
air in the valley, the locations on the slope profit from a comparatively warm nocturnal climate at such places (Chickering 1884, Kamiguchi et al. 1997) due to the flux of sensible heat from the air towards the surface at night. However, this effect is less pronounced over forest, where the rough vegetation decelerates cold-air drainage flow considerably compared to open and more exposed grassland. The mean difference in sensible heat fluxes between forest and grassland (42 W m$^{-2}$; Table 1) roughly corresponds to one third of the net radiative energy gained by the combined albedo and temperature effects.

The land-use pattern investigated here is typical for the subalpine zone of the Alps with a humid climate and is maintained thanks to the subsidies that local farmers receive from the Swiss government. Grasslands in this elevation are often kept as mixed pastures and meadows. This keeps the optically determined leaf area index (LAI) of grassland relatively low (LAI ± standard error was 2.2 ± 0.6 in August to 1.1 ± 0.2 in October) compared to coniferous forest (estimated to be around 8–12), thereby limiting maximum evapotranspiration rates of the grassland. In contrast to the findings from the boreal forest experiments in North America (Sellers et al. 1995, Sellers et al. 1997, Hall 1999, Hollinger et al. 1999), Europe (Grelle et al. 1999) and Siberia (Kelliher 2001) evapotranspiration rates observed at our location do not exhibit a strong control of coniferous vegetation over water losses. Due to ample orographic precipitation water supply of the plants does not appear to be a limiting factor. The high evapotranspiration rate of forest that corresponds to 91% of the net radiative energy received at the surface indicates that the supply of solar energy is a limiting factor on this North-facing slope with a reduced sky-view factor, late sunrises and early sunsets even in the summer. Without management such grasslands would disappear due to regrowth of forest. Government census data (BfS 2002) document a natural regrowth of forests in Switzerland that accounts for 86.8% of the total increase in forest area (+1.6% in the past 12 years) and is mainly due to the abandonment of pastures in the Alps (BfS 2002:126–133). The feedbacks to climate of such a regrowth is expected to lead to greater evapotranspiration from the vegetation and thus to increased atmospheric moisture, and potentially also to increased precipitation.

On the diurnal time scale the increase in evapotranspiration leads to a decrease in sensible heat flux during daytime, but not so much during the night (Figures 7 and 8). The overall mean effect (Table 1, Figure 9) is however suggesting the opposite, namely an increase in mean temperature due to a mean increase in sensible heat flux. Whether this should be considered a positive or negative effect for the subalpine elevation zone remains to be investigated in more detail since the overall effect is mainly dominated by nighttime conditions.

4 Discussion

We used the BREB method because of its simplicity, its relatively low cost and low power requirements. However, it should be noted that despite its widespread application the BREB method is currently more and more replaced by eddy covariance flux measurements (see e.g. Baldocchi et al. 2001). Stannard (1997) addresses in detail that the two psychrometers mounted at different heights do not have exactly matching footprint areas. That is, the upper
pair of sensors always measures a larger surface area than the lower pair of sensors. This could lead to artifacts when applying the BREB method in heterogeneous terrain. We tried to minimize such problems by measuring relatively close to the canopy such that the footprint for both sensor pairs should always cover the same surface type (grassland or forest). However, when it comes to the question of accuracy of such measurements one should not overestimate the performance of that method. We consider our approach to be well suited for a pilot study as presented here, but the reader should consider that the accuracy of the flux values reported in Table 1 using the standard error approach only addresses the random error and not the largely unknown systematic errors as discussed by Stannard (1997). Nevertheless, our season-long measurements should allow a qualitative assessment of how changes in land management practice would influence the climate system.

A scenario without cattle grazing but with continued hay harvest would certainly increase the leaf area index and thus evapotranspiration from grasslands during a significant part of the vegetation period. Although it is not expected that this would more than double current evapotranspiration from grassland, such an extreme assumption could eliminate the difference in evapotranspiration rates between forests and grasslands, and could therefore potentially have as strong an effect as is expected for the summer season from a grassland to forest transition.

Feedbacks that occur during the summer are the most relevant ones for assessing potential implications for the return period and intensity of natural hazards in subalpine areas. Increased evapotranspiration from forests compared to grasslands under such conditions suggests that forest vegetation contributes to a better drainage of the topsoils and might therefore help to reduce the potential for shallow landslides under otherwise unchanged conditions. The newest IPCC vulnerability report (Parry et al. 2007) however sees the risk of increased droughts to be noteworthy in mountain areas such as the Alps where warmer and drier conditions are projected (Beniston 1994; Beniston et al. 1997; OcCC 2007), which could induce forest dieback in continental climates, particularly in the interior of mountain ranges (Fischlin et al. 2007, p. 232).

On the global scale deforestation, primarily the conversion of forests to croplands and pasture is changing the global radiative forcing (Forster et al. 2007, p. 132 & 182). Because the dark forests are replaced by brighter vegetation types, the albedo effect counteracts the effect of increasing greenhouse gas concentrations, and is estimated at –0.2 (range –0.4 to 0.0) W m$^{-2}$ globally (Solomon et al. 2007, p. 4). This is a relatively small component compared to the sum of the three major greenhouse gases CO$_2$, CH$_4$, and N$_2$O, which represent an anthropogenic radiative forcing component of +2.30 (range +2.07 to +2.53) W m$^{-2}$ (Solomon et al. 2007, p. 3) accumulated since pre-industrial times.

In the Alps the process of forest expansion is just working in the opposite direction of what is observed on average on the global scale. The measurements we made in 1999 are only representing summer conditions, and thus our measured differences between grassland and forest cannot be directly compared with the values presented in the newest IPCC report. But a back-of-the-envelope calculation can provide a reasonable estimate of how important land use changes from grassland to forest might be in the subalpine zone of the Alps. To be conservative, we assume that the difference in net radiation of 110 W m$^{-2}$ between forest and
grassland is only relevant for the three summer months. With this assumption the mean difference reduces to 27 W m\(^{-2}\) on an annual basis. As of 1992/1997 the share of forests in Switzerland was 28.2% \((BfS 2002)\), and thus the reported increase in forested areas of +1.6% in 12 years corresponds to 0.45% of the total Swiss land surface. This value multiplied by the 27 W m\(^{-2}\) annual difference of net radiation between forest and grassland yields 0.12 W m\(^{-2}\) as the potential radiative forcing effect related to land use changes from grasslands to forests.

Still, this number cannot be directly compared with the IPCC numbers, because the anthropogenic forcing is expressed as the change since the industrialization began (around 1750), whereas we have computed the potential radiative forcing for the forest increases that occurred during the past 12 years. In order to be comparable, the radiative forcing for CO\(_2\), CH\(_4\), and N\(_2\)O must thus be computed from the differences between the fourth IPCC assessment (data from 2005) and the values from the third assessment report (data from 1998). In that time the radiative forcing of the three most important greenhouse gases has increased from 2.09 to 2.30 W m\(^{-2}\) (computed from data presented by Forster et al. 2007, p. 141), corresponding to an increase of 0.36 W m\(^{-2}\) in 12 years. Thus, the land use changes as they currently occur in the subalpine zone of Switzerland potentially enhance the global-scale radiative forcing by roughly one third (0.12/0.36) on this local to regional scale.

Observed air temperatures in Switzerland show an increase by 1.47°C during the period 1900–2006, whereas the global mean temperature only increased by 0.87°C in the same time \((North et al. 2007)\). Thus the increase in Switzerland is almost 70% above the global average. Our rough calculations considering the land use change from grassland to forest as one possible reason for this greater-than-average warming cannot account for such a strong increase, although our calculations indicate that it is very likely that a certain share of this temperature increase might be explained by forest expansion.

## 5 Conclusions

Our comparative study of the energy balance over a grassland and a coniferous forest site in the subalpine zone of the Bernese Oberland suggests that evapotranspiration rate from forest is 1.9 times that of grassland during the growing season months July–October. An important reason for this difference is the albedo effect. The darker forest has 3.4 times the net energy available for sensible heat flux, evapotranspiration, and ground heat flux as compared to grassland. Of this surplus in net energy roughly two thirds are used for enhanced evapotranspiration (factor 1.9 between forest and grassland), whereas the other one third is used as sensible heat flux, with only a minor influence on ground heat flux.

In comparison with other factors that influence global climate change, such as the increase in greenhouse gas concentrations since pre-industrial times the potential radiative forcing from land use changes from grassland to forest cannot be neglected, but clearly cannot account for the overall warming observed in Switzerland during the past century, which is well above the global average rate of temperature increase.
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Summary: Evapotranspiration and energy flux differences between a forest and a grassland site in the subalpine zone in the Bernese Oberland

Vegetation plays a key role for local and regional climates, since the transpiration of the green biomass that is closely linked with photosynthetic assimilation consumes a considerable share of available energy. Thus, land use changes from grassland to forest potentially also lead to changes in the near-surface climate via the change in surface energy budgets. Typically, model estimates assume a higher evapotranspiration from forests than from grasslands in mountain areas, but measurements are scarce. For the Spissibach Natural Hazards Research Catchment east of Thun, Switzerland, we quantified the climatologically relevant surface energy fluxes during the summer of 1999 of a grassland and a 15-yr old Norway spruce forest in the subalpine elevation zone.

The coniferous forest under investigation with the Bowen-ratio approach yielded a 1.9 times greater evapotranspiration than a grazed grassland at similar elevation, slope and aspect. The darker forest surface absorbed more energy than grassland during the day. Since most of this energy surplus, however, was used for evapotranspiration, less sensible heat remained than above the grassland. This leads to generally cooler daytime conditions over forest than grassland. In contrast, in the seasonal average the forest was characterized by higher mean sensible heat fluxes, mainly because open areas such as grasslands loose more sensible heat to cold-air drainage flows at night. The dominance of these nocturnal conditions in the mean energy budget leads to the finding that forests tend to yield higher mean temperatures than grasslands, despite the lower peak daytime temperatures.

Zusammenfassung: Unterschiede der Verdunstung und Energiebilanz eines Waldes und eines Graslands in der subalpinen Zone im Berner Oberland


Der mit der Bowen-Ratio Methode untersuchte Fichtenwald verdunstete im Vergleich mit einer typischen Weide (mit anschliessender Wieslandnutzung im Herbst) auf ähnlicher Seehöhe, Exposition und Hangneigung rund 1,9-mal soviel Wasser während der Vegetationsperiode. Zwar nimmt der dunklere Wald tagsüber und im Mittel mehr Energie auf als Weideland. Da
aber ein Grossteil dieser Energie in Verdunstungswärme umgewandelt wird, verbleibt tagsüber weniger fühlbare Wärme über dem Wald, was zu tendenziell kühleren Bedingungen gegenüber Weideland führt. Im Mittel verhält es sich jedoch genau umgekehrt: die Weiden verlieren deutlich mehr fühlbare Wärme während der Nacht (Kaltluftabfluss), so dass wegen der Dominanz der nächtlichen Differenzen die Wälder eher wärmer sind als Weideland.

Résumé : Différences d’évapotranspiration et du flux d’énergie de surface entre une forêt et un pâturage dans la zone subalpine de l’Oberlande Bernoise

Le climat local et régional est contrôlé d’un part important de la végétation. La transpiration des plantes vertes est directement liée avec l’assimilation photosynthétique en consommant une fraction importante de l’énergie disponible à la surface de la terre. Alors, un replacement d’un pâturage ou d’un pré par une forêt devrait avoir un effet au climat de la couche atmosphérique touchant la surface. En général les modèles quantifient une évapotranspiration élevée d’une forêt de montagne en comparaison avec des prés ou pâturages, mais il n’existent pas assez de mesures expérimentales pour élaborer cette thèse quantitativement. Dans cet article nous présentons nos mesures de l’été 1999 d’une pâturage et une forêt composée de sapins âgés d’environ 15 ans dans le site de recherche des hasards naturels du Spissibach à l’est de Thoune, Suisse, dans la zone subalpine.

Les conifères dont on obtenait les flux d’énergie utilisant la méthode de Bowen-ratio avait une évapotranspiration élevée de 1.9 fois le flux mesuré sur le pâturage d’altitude, pente et exposition semblables. La forêt de couleur plus foncée absorbait plus d’énergie pendant le jour en comparaison avec le pâturage. Mais parce-que l’évapotranspiration consommait la majorité du surplus de flux énergétique, le flux de chaleur sensible était diminué au forêt en relation du pâturage. La conséquence pour la forêt est un climat moins chaud pendant le jour qu’expérience la pâturage. A l’échelle d’une saison la situation est renversée avec plus de flux de chaleur sensible au moyen de la saison parce-que le pâturage avec sa végétation basse est plus ouverte pour un flux de chaleur négative et des mouvements d’air froide pendant la nuit qui constituent un export essentiel d’énergie à disposition à l’écosystème. Le rôle dominant des conditions nocturnes élèvent le moyen de température d’air du forêt au dessus de la température moyenne de la pâturage, autant que les maximums de jours étaient classifiées à revers.

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Table 1: Comparison of seasonal means measured at the grassland and forest sites (above and below canopy). All means ± standard errors were derived from a subset of days where all three stations collected data simultaneously (July–October 1999).


<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Days</th>
<th>Grassland</th>
<th>Forest top</th>
<th>Forest floor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature</td>
<td>ºC</td>
<td>74</td>
<td>11.08 ± 0.52</td>
<td>12.21 ± 0.54</td>
<td>11.12 ± 0.50</td>
</tr>
<tr>
<td>Wet bulb temperature</td>
<td>ºC</td>
<td>72</td>
<td>9.54 ± 0.52</td>
<td>10.14 ± 0.47</td>
<td>9.68 ± 0.46</td>
</tr>
<tr>
<td>Soil temperature</td>
<td>ºC</td>
<td>100</td>
<td>13.14 ± 0.33</td>
<td>a</td>
<td>11.83 ± 0.28</td>
</tr>
<tr>
<td>Soil moisture content</td>
<td>vol. %</td>
<td>105</td>
<td>51.6 ± 0.4</td>
<td>a</td>
<td>57.8 ± 0.3</td>
</tr>
<tr>
<td>Evapotranspiration rate</td>
<td>mm d⁻¹</td>
<td>68</td>
<td>2.6 ± 0.3</td>
<td>4.9 ± 0.4</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>Net radiation flux</td>
<td>W m⁻²</td>
<td>68</td>
<td>46 ± 11</td>
<td>156 ± 11</td>
<td>12 ± 1</td>
</tr>
<tr>
<td>Sensible heat flux</td>
<td>W m⁻²</td>
<td>68</td>
<td>−29 ± 7</td>
<td>13 ± 3</td>
<td>1.0 ± 0.4</td>
</tr>
<tr>
<td>Latent heat flux</td>
<td>W m⁻²</td>
<td>68</td>
<td>74 ± 10</td>
<td>142 ± 11</td>
<td>12 ± 1</td>
</tr>
<tr>
<td>Ground heat flux</td>
<td>W m⁻²</td>
<td>68</td>
<td>1.1 ± 0.8</td>
<td>a</td>
<td>−0.1 ± 0.4</td>
</tr>
</tbody>
</table>

*measured on forest floor only
Figure 1: Map of Switzerland showing the elevation range 800–1600 m a.s.l. north of the Alps for which our investigation should be representative. The study area is shown by a black square.

Figure 2: View from Morgenberg mountain top down to Spissibach Natural Hazards research catchment above the town of Leissigen on the bank of Lake Thun. View direction is roughly towards the North. The grassland (G) and forest (F) sites are marked by an arrow and a diamond. / Blick vom Gipfel des Morgenberghorns über das Spissibach Wildbach-Forschungs-Einzugsgebiet oberhalb des Dorfes Leissigen am Thunersee. Blickrichtung ist ungefähr gegen Norden. Die untersuchte Alpweide (G) und der Fichtenwald (F) sind mit Pfeil und Raute eingezeichnet.
Figure 3: Detailed view of the grassland site with the 10-m wind mast in the center of the enclosure near the cabin of Alp Fulwasser. Radiation instruments including the net radiation sensor are seen to the left on a boom at $\approx 2$ m above ground level. The upper psychrometer is seen between this boom and the small solar panel. The lower psychrometer is a few centimeters above the grass canopy top. / Detailansicht des Alpweidestandorts bei der Alp Fulwasser. Am 10 m Windmast mit Feldschrank an der Basis ist auf $\approx 2$ m Höhe ein nach links ausgerichteter Ausleger mit den Strahlungsmessgebern zu sehen. Das obere Psychrometer befindet sich zwischen diesem Ausleger und dem kleinen Solarpanel. Das untere Psychrometer ist wenige Zentimeter oberhalb der Grasvegetation positioniert.
Figure 4: The instrumentation above the forest canopy dangling from a cable that bridges between the location where power supply and data acquisition were located and a nearby rising old tree. The younger forest canopy above which the measurements were carried out is seen below the instruments. / Messinstrumente über dem Fichtenjungwuchs, aufgehängt an einem Drahtseil, das zwischen der Stelle, an der die Stromversorgung und Datenerfassung aufgebaut werden konnte und einem freistehenden Altbaum gespannt wurde.
Figure 5: One of the two micro-Bowen-ratio systems used above the forest floor. Measurements must represent the local gradients of temperature and moisture to be useful for the calculation of the sensible heat flux and evaporation of the forest floor surface. / Eines der beiden Mikro-Bowen-Ratio-Systeme, die über dem Waldboden eingesetzt wurden. Die Messungen müssen den lokalen Temperatur- und Feuchtegradienten über dem Waldboden repräsentieren, damit eine Berechnung des fühlbaren Wärmestromes und der Verdunstung des Waldbodens möglich ist.
Figure 6: Daily means during the growing season of 1999. Air temperatures (a), including data from Interlaken weather station, and energy fluxes (b-e) as measured in a subalpine spruce forest and a managed grassland. Bold lines are 5-day running means. Significant flux differences between forest and grassland were found for net radiation (b), sensible (c) and latent (d) heat flux. Mean heat flux to the ground (e) was small for both vegetation types, and indicates the expected seasonal evolution with a less pronounced effect under the forest canopy. Note the enlarged vertical scale in panel (e).
Figure 7: Mean diurnal fluxes during July 1999 at the grassland (thick line with open squares), over the forest (thin line with solid triangles), and on the forest floor (broken line with open triangles). Shown are hourly averages of (a) net radiation; (b) sensible heat flux; (c) latent heat flux; (d) ground heat flux. / Mittlere Tagesgänge der Flüsse im Juli 1999 über Grasland (fette Linie mit Quadraten), über Wald (dünne Linien mit schwarzen Dreiecken) und am Waldboden (gestrichelte Linie mit weissen Dreiecken); (a) Nettostrahlung; (b) fühlbarer Wärme-fluss; (c) Verdunstungswärme-fluss; (d) Bodenwärme-fluss.
Figure 8: Same as in Figure 7 but for August 1999. / Wie in Abbildung 7 für August 1999.
Figure 9: Monthly means of energy flux components during the growing season of 1999. Error bars denote ±1 standard error. Data collection at the forest site started in July 1999, therefore only the grassland data are shown for the month of June.