Ecosystem Thermal Buffer Capacity as an Indicator of the Restoration Status of Protected Areas in the Northern Ethiopian Highlands

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Abstract

Restoration status of forest rehabilitation areas can be assessed by comparing their ecosystem characteristics with those of a reference system, most often what is considered the natural climax vegetation. However, comprehensive measurements needed for a traditional vegetation description are often hard or impractical in complex (sub)tropical ecosystems. Therefore, an alternative approach is the identification of simple indicators of ecosystem integrity. The use of such indicators can speed up the availability of resource inventories and thus contribute to the accelerated implementation of successful rehabilitation practices. Thermal buffer capacity (TBC) of ecosystems has been previously proposed as an overall indicator of ecosystem integrity. In this article, sequential surface-temperature measurements are proposed as a method for TBC assessment of different land-use types. Surface temperatures of seven land units in central Tigray (northern Ethiopia), each with a uniform land-use type (degraded and bushy grazing land, enriched and non-enriched rehabilitation area, and forest), were measured with a hand-held infrared thermometer in the rainy and the dry season. Surface-temperature models were derived by means of quadratic regression. Cross-correlation functions were calculated for all possible pairs of land-unit time-series data. Instantaneous heat-up rates, average TBC, and accumulated heat load were calculated. Repeated-measures analysis of variance was used to test the effect of aspect and protection status on TBC. Kruskal–Wallis one-way analysis of variance by ranks for small samples was used to test the significance of differences in heat-up rates and heat load among land-use groups. Time lags between land-unit surface temperatures are caused by differences in aspect rather than land-use type. Protection status and aspect have a significant effect on the average TBC. Results clearly demonstrate a differentiation between protected (low heat-up rate) and non-protected areas (high heat-up rate). Overall ranking suggests that the remnant forest has the highest TBC of all surveyed land-use types, followed by the enriched protected area. Results of this study show that TBC quickly responds to area closure and can therefore be used to monitor the development of protected areas. It is strongly recommended that a detailed monitoring strategy for protected areas on the basis of this technology be devised, validated, and finally transferred to the local communities.

Key words: closed area, ecosystem restoration, Ethiopia, exergy, grazing exclosure.

Introduction

Forest degradation and subsequent soil erosion are major environmental problems in many mountain areas (Reasoner et al. 2001), especially in the tropical and subtropical zones. Conversely, forest restoration is considered a powerful instrument to rehabilitate degraded lands. The factors that affect the rate of restoration include initial site characteristics, management practices, and, if applicable, plantation design (Wunderle 1997). By comparing their ecosystem characteristics with those of forest remnants, one can assess the current restoration status of rehabilitation areas. This can be done in various ways. Usually, sample plots are laid out in a stratified random design to describe vegetation composition and structure and its relation to environmental variables such as soil characteristics and topology. Results are then compared to a similar dataset of a reference system, most often to what is considered the natural climax vegetation. However, ecosystems in the tropics and subtropics commonly possess a high degree of structural and biological diversity, making comprehensive measurements hard or impractical. Therefore, an alternative approach is the identification of simple indicators of ecosystem integrity. The use of such indicators can speed up the availability of resource inventories and thus contribute to the accelerated implementation of successful rehabilitation practices. Many existing ecological

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more slowly, and, consequently, show a cooler surface systems dissipate solar radiation more effectively, heat up authors have suggested that undisturbed natural climax systems are expected to dissipate solar exergy, thermal indicators are expected to provide relevant information on the restoration stage of an ecosystem. The research was carried out in Mai ba’ati (13°38’ N, 39°13’ E; 2,200–2,350 m above sea level), in the Dega Tembien district (woreda) of the central highlands of Tigray, northern Ethiopia. Soil type and rainfall–temperature relation are the primary factors that determine the pattern of natural vegetation and potentials for agricultural and forest production. The rainfall–temperature relation principally varies with altitude, but recent research pointed out that the slope aspect plays an even more significant role in the spatial distribution of rainfall. Slopes oriented to the east tend to receive more rainfall than those oriented to the west because of rain shadow effects resulting from the prevailing east–west winds during the rainy season (kremt). The main soil parent materials in the region are basalt lava and mudflows, sedimentary sandstone and calcareous rocks, and lacustrine silified limestone. The soils in the study area are strongly linked to topography and parent material with Vertisols and soils with vertic properties dominating the soilscape in plateau situations wherever basalt is present in the soil profile. In the upper reaches, Leptosols are dominant in association with Vertic Cambisols. The footslopes comprise Vertic Calcisols, Calcaric Phaeozems, Vertic Cambisols, and Calcaric Regosols. The natural pre-disturbance vegetation of the area is Podocarpus falcatus (Thunb.) Mirb. (East African yellowwood, indicators are defined as the presence of a taxon or a group of taxa characterized by a distinctive response to a certain set of environmental variables (Burley & Gauld 1994). The measurement of these indicators depends on a high level of knowledge and experience, hindering a wide applicability. According to Bendorichio and Joergensen (1997), the thermodynamic features of an ecosystem might be more appropriate to capture its overall properties. In this article, thermal buffer capacity (TBC) is proposed as an overall indicator of ecosystem restoration status, summarizing underlying biotic and abiotic factors of increased control of the biocenosis over the energy and material flows through the system (Muys et al. 2001, 2003). Thermal buffer capacity is an indicator related to the thermal response number (TRN) proposed by Luvall and Holbo (1989) to distinguish between land-use types (LUT) with different degrees of integrity. Thermal response number of ecosystems can be computed from thermal remote sensing data and measurements of net solar and long-wave radiation. Muys et al. (2001) proposed thermal indicators such as surface temperature and TRN to assess human land-use impact in the framework of life cycle assessment (LCA) of products from the agriculture and forestry sector. The value of these thermal indicators can be explained by the ecosystem exergy theory. Exergy is defined as energy free of entropy, which consequently is able to do work. Schneider and Kay (1995) formulated the hypothesis that ecosystems with the highest maturity and functional complexity contain the highest exergy level and consume the incoming solar radiation in the most efficient way. As summarized by Wagendorp et al. (2001), the functional goal of all ecosystems is to maximize dissipation or buffering of exogenic exergy fluxes by maximizing the internal exergy content in the form of biomass, biodiversity, and complex trophic networks. As a consequence, the authors aptly stated that natural climax systems are expected to have the highest site-specific exergy level and that human impact may decrease ecosystem exergy because of degradation processes. Similarly, ecosystem restoration may increase the speed at which natural systems reconstruct their exergy level and regain control over radiation, water, and nutrient fluxes. Because solar radiation is the main exogenic exergy flow in many terrestrial ecosystems and the thermal features of an ecosystem reveal its ability to dissipate solar exergy, thermal indicators are expected to provide relevant information on the restoration stage of an ecosystem.

The use of thermal information is known to be beneficial to the evaluation of ecosystem physiological activity, functioning, and health (Jones 1999; Moran 2000; Samson & Lemeur 2000; Allen et al. 2001). The surface temperature of an ecosystem is believed to give a spatially integrated response of all factors that influence the physiological and physical canopy behavior. Several authors have suggested that undisturbed natural climax systems dissipate solar radiation more effectively, heat up more slowly, and, consequently, show a cooler surface temperature than other systems at the same site (Schneider & Kay 1995; Allen et al. 2001; Wagendorp et al. 2001). The rate of change in surface temperature can be used as a value that reveals how the non-radiative fluxes react to changing radiant energy inputs (Luvall & Holbo 1990). All this suggests that time-series measurements of surface temperatures of different LUT can yield a good estimation of their thermal buffering capacity and, hence, their restoration status. This multi-temporal approach facilitates a detailed study of the relationship between incoming exergy and its degradation by the ecosystem (Luvall & Holbo 1989, 1990; Allen et al. 2001; Kay et al. 2001). Surface temperatures can be measured with thermal infrared (IR) sensors mounted on platforms ranging from space-borne, airborne to ground measurements (hand-held IR thermometers). Infrared thermometers measure the surface temperature of an object by sensing its emitted, reflected, and transmitted IR radiation (8–14 µm) and translating the information into an integrated temperature reading, taking into account the differences in emissivity between surfaces.

The purpose of this study was to (1) develop a method for TBC assessment of ecosystems on the basis of sequential surface-temperature measurements with a hand-held IR thermometer and (2) evaluate the TBC of different LUTs as a single indicator of forest restoration status.

Site Description

The research was carried out in Mai ba’ati (13°38’ N, 39°13’ E; 2,200–2,350 m above sea level), in the Dega Tembien district (woreda) of the central highlands of Tigray, northern Ethiopia. Soil type and rainfall–temperature relation are the primary factors that determine the pattern of natural vegetation and potentials for agricultural and forest production. The rainfall–temperature relation principally varies with altitude, but recent research pointed out that the slope aspect plays an even more significant role in the spatial distribution of rainfall. Slopes oriented to the east tend to receive more rainfall than those oriented to the west because of rain shadow effects resulting from the prevailing east–west winds during the rainy season (kremt). The main soil parent materials in the region are basalt lava and mudflows, sedimentary sandstone and calcareous rocks, and lacustrine silified limestone. The soils in the study area are strongly linked to topography and parent material with Vertisols and soils with vertic properties dominating the soilscape in plateau situations wherever basalt is present in the soil profile. In the upper reaches, Leptosols are dominant in association with Vertic Cambisols. The footslopes comprise Vertic Calcisols, Calcaric Phaeozems, Vertic Cambisols, and Calcaric Regosols. The natural pre-disturbance vegetation of the area is Podocarpus falcatus (Thunb.) Mirb. (East African yellowwood,
Podocarpaceae)—Juniperus procera Hochst. ex Endl. (East African pencil cedar; Cupressaceae) forest (Friis 1992; Teketay & Granström 1997), which was cleared at about 500 BCE (Darbyshire et al. 2003). In the whole country, only tiny fragments of the original Afromontane forest vegetation remain, usually on inaccessible steep or rocky terrain (Teketay & Granström 1997) or otherwise less accessible land such as sacred church groves. Wilson (1977) summarized the main secondary vegetation types in central Tigray from various authorities (the most important being Pichi-Sermolli 1957). Three vegetation types presently or potentially occurring in the study area were defined as follows: (1) montane evergreen thicket and scrub (two types: one type with Euphorbia candelabrum Tremaut. ex Kotschy [Candelabra tree, Euphorbiaceae] on shallow soils and another type with species of several genera including Carissa edulis (Forssk.) Vahl [Natal plum, Apocynaceae], Euclca racemosa ssp. schimperi (A. DC.) White [Bush guarri, Ebenaceae], Rhus spp. [Anacardiaceae], Maytenus senegalis (Lam.) Exell. [Red spikethorn, Celastraceae], and Dodonea angustifolia L. f. [Sand olive, Sapindaceae]), (2) montane savanna (usually with Acacia spp. [Fabaceae] and Olea europaea ssp. cuspidata (Wal. ex G. Don) Cif. [African wild olive, Oleaceae] in dominant positions), and (3) montane dry evergreen forest (with J. procera and O. europaea).

Impoverishment of the increasing highland population and their search for subsistence income has led to a second wave of massive deforestation, site degradation, and soil erosion since approximately CE 1700 (Darbyshire et al. 2003). Forest remnants often were over-exploited by systematic fuel wood extraction, logging of valuable timber, illegal grazing, and unintentional fire. Because of this massive environmental degradation, recurrent droughts have a stronger negative impact on agricultural production and the environment (i.e., over-grazing, cracking of vertisols, groundwater depletion, and increased soil erosion) (Nysen et al. 2004). Pilot reforestation schemes have been established since 1970. They usually involved terracing of the slopes and planting of (mainly exotic) seedlings grown in nurseries but were expensive and disturbed the native relict vegetation.

Much of the success of the forestation on terraces lies in the natural regrowth of weedy vegetation following exclusion of grazing animals. For that reason, several areas have been closed to livestock since the mid-1980s. Recently, the Relief Society of Tigray (REST), a rehabilitation nongovernmental organization (NGO), initiated the establishment of such protected areas on a region-wide scale. Although the organization has clearly stated its operational objectives, it does not yet have the scientific or financial capacity to monitor underlying processes and vegetation change in protected areas (Aerts et al. 2001). Area closure in the framework of natural forest restoration and soil conservation is a typical example of a major land-use change and is therefore considered as a key element in this study.

Methods

Data Collection

The study site is situated on a steep-to-moderately-steep slope distinctively demarcated by a calcareous cliff and situated downhill from a cropland area on Cambic Vertisols and related soil groups. The area under study could be roughly divided into a slope with southeast aspect in the west of the study area and a slope with southwest aspect toward the east of the study area (Fig. 1a).

Contemporary land use was assessed by means of detailed Global Positioning System (GPS) measurements (GeoExplorer III, Trimble Navigation Limited, Sunnyvale, CA, U.S.A.). The positions of prominent point and linear features such as large trees, boulders, gullies, contour stone bunds, and footpaths were recorded for further use.
as ground control points (GCPs). A 2001 land-use map was compiled (Fig. 1b). Information about former land use and land-use changes was derived from semistructured interviews with 15 randomly selected resident senior farmers. Former land-use maps were derived from interpretation of 1:50,000-grayscale stereo-couple 1964 and 1994 aerial photographs. The photographs were scanned and integrated in the Geographical Information System (GIS) environment (ArcView GIS 3.2a, ESRI, Redlands, CA, U.S.A.) after rubber sheeting (Warp Environment for ArcView GIS, ESRI) and geo-referencing (Image Georeferencing Tools for ArcView GIS, George Raber, USC, Columbia, SC, U.S.A.). Land use of 1964 and 1994 was digitized on-screen. 

Five contrasting LUTs were retained for further investigation in this study: a 7.65-ha closed-canopy secondary forest surrounding a Coptic church (hereafter referred to as church forest, Fch), protected area (Fpa), protected area enriched with *Eucalyptus* spp. (Myrtaceae) (FpaE), bushland with allowed grazing and firewood collection (Gbu), and degraded bushland with allowed grazing and firewood collection (Gde). Settlement areas, controlled grazing and browsing areas, farmsteads with cropland, firewood collection (Gde), settlement areas, controlled grazing and browsing areas, farmsteads with cropland, and cropland under extensive irrigation were not taken into further consideration.

Surface temperatures of seven land units (LU), blocks with uniform LUT, were measured from two observation points located on a cliff facing the study site from the north (Fig. 1b). Four units were located on the western slope (W) with southeast aspect: FpaW (20.40 ha), FpaE (0.97 ha), GbuW (3.37 ha), and GdeW (26.78 ha). The three other units were situated on the eastern slope (E) with southwest aspect: FchE (7.65 ha), FpaE (2.98 ha), and GdeE (0.57 ha). A hand-held noncontact IR thermometer (Infra-pro 3 WD-35629-20, Oakton Instruments, Vernon Hills, IL, U.S.A.) with a temperature range of −32 to 600°C (accuracy 1/10 ± 1°C), a spectral response from 8 to 14 μm, and a distance-to-spot size (D:S) of 30:1 was used. The sensor has the capability to capture 90% of the outgoing long-wave radiation $L^\uparrow$ and yields a surface temperature $T_s$ directly in degree centigrade by using the Stephan–Boltzmann equation:

$$T_s = \sqrt{\frac{L^\uparrow}{\varepsilon \cdot \sigma}} = 273.15,$$

where $T_s$ is the surface temperature in degree centigrade, $L^\uparrow$ is the outgoing long-wave radiation, $\sigma$ is the Stephan–Boltzmann constant, and $\varepsilon$ is the emissivity.

All measurements were carried out with a fixed assumed IR emissivity of 0.95, a standard value for vegetation surfaces ($\varepsilon = 0.60$ for desert surface [Petitcolin et al. 2002]; $\varepsilon = 0.95$ for vegetated areas [Nichol 1994], grass [Brutsaert 1982], and leaves [Jones et al. 2002]; $\varepsilon = 0.98$ for closed-canopy forest [Samson & Lemuer 2000]).

For both slopes, the distance from the sensor to the LU ranged from 320 to 560 m, with a maximum elevation difference of 130 m. Accounting for the slope (45°) and the narrow field of view (FOV = 2°) of the sensor, it could be calculated that the spot size of the sensor ranged from 15 to 26 m², well within the minimal surface area of the selected LUs (5,700 m²). The layout of the study area allowed for near-perpendicular alignment of land surface and sensor, by positioning the sensor at the eastern end of the cliff when measuring LUs on the western slope and vice versa. Approximately every half hour, four surface temperatures (each the average of a 10-second continuous measurement) were recorded for each LU. Measurements were carried out at the end of the rainy season in late September 2001 and in the dry season in May 2003 between 07 and 16 hours, covering the period of complete insolation of the LUs on both slopes. Air temperatures in full shade during measurements ranged between 17 (morning) and 25°C (noon) in the wet season and 19.5 and 29°C, in the morning and noon, respectively, in the dry season. During periods of partial shading due to overhead clouds, measurements of LUs were delayed for some minutes (because shading temporarily caused a major surface-temperature decrease of the LUs). Two 20 × 20-m² sample plots were laid out in each of the seven LUs, and their vegetation composition was recorded as presence/absence data.

**Statistical Analysis**

Time-series data can be defined as a sequence of values for a single variable (in this case, the surface temperature of a LU) where each row in the dataset represents an observation at a different time, at equally spaced time intervals. Surface-temperature measurements on the field, however, are rarely perfectly timed, especially when data acquisition requires continuous movement along rugged terrain or when clouds temporarily prevent full insolation of the LUs. Therefore, second-order polynomial temperature functions were developed from the field data by means of quadratic regression. Surface-temperature estimates at equally spaced time intervals (half hourly between 07 and 17 hours) were derived to create a modeled dataset fit for further analysis (Table 1):

$$T_s = f(t) = at^2 + bt + c,$$

where $T_s$ is the surface temperature (in degree centigrade) and $t$ is time (minutes) ($t = 0$ at 07 hours).

To determine whether the observations of one series were correlated with the observations of one or more other series at various time lags, we calculated cross-correlation functions (CCF) for all possible pairs of land-unit time-series data in the dry and rainy season. A two-standard-error confidence limit was used.

First-derivation functions of the modeled quadratic surface-temperature functions were calculated to evaluate
instantaneous heat-up rates \( T' \) (degree centigrade/minute):

\[
T'_i = \frac{dT_s}{dt} = 2at_i + b. \tag{3}
\]

Three parameters that characterize the thermal response of LUs were derived from the instantaneous heat-up rate functions: (1) the absolute slope of the heat-up rate function \(2at\), (2) the initial heat-up rate \(b\), and (3) the intercept \(-b/2a\) equal to time \(t\) when \(T_S\) reaches its local maximum \(T_{\text{max}}\) or the vertex of the surface-temperature function. The effect of land use on these parameters was analyzed for three groups (forest \(n = 1\), protected areas \(n = 3\), and open grazing land \(n = 3\)) by means of Kruskal–Wallis one-way analysis of variance by ranks for small samples (Siegel & Castellan 1988).

As mentioned above, there are reasons to believe that LUs with a low TBC will heat up more during a certain time span as compared with LUs with a high TBC. Accordingly, their heat-up rate will be higher. Therefore, the inverse heat-up rate can be interpreted as an estimator of TBC (Eq. 4) and an estimation of the average TBC over a time interval of \(i\) minutes (minutes/degree centigrade) can be made on the basis of temperature measurements (Eq. 5):

\[
\frac{dT}{dT}\Big|_{T_{\text{max}}} = \frac{\Delta t}{\Delta T_s} = \frac{t_i - t_0}{T_s - T_0}. \tag{4}
\]

\[
\frac{\Delta T}{\Delta t}\Big|_{T_{\text{max}}} = \frac{T_s - T_0}{t_i - t_0}. \tag{5}
\]

Repeated-measures analysis of variance was applied to test the effect of aspect and protection status (open grazing land vs. protected area) on mean TBC at noon (TBC\(_{12}\)) and at \(T_{\text{max}}\) (TBC\(_{\text{vertex}}\)). Season (dry and rainy) was used as a within-subject effect.

Accumulated heat load \(Q\) in degree hours was calculated by integrating under the modeled temperature curves (Eq. 6):

\[
Q = \frac{1}{60} \int_0^i f(t)dt = \frac{1}{60} \left[ \frac{a}{3} t^3 + \frac{b}{2} t^2 + ct \right]_0^i. \tag{6}
\]

Subsequently, relative inefficiency of energy digestion was derived by subtracting the heat-load of the reference system Fch from the heat load of other LUs. The effect of land use on relative inefficiency was analyzed for three groups (enriched protected area \(n = 1\), other protected areas \(n = 2\), and open grazing land \(n = 3\)) by means of Kruskal–Wallis one-way analysis of variance by ranks for small samples (Siegel & Castellan 1988).

Results

Land-Use Change

Land-use-change detection showed clear differences in land-unit history. Dense forest has continuously occupied the church forest FchE since 1964 and, more than likely, much longer—if not permanently. *Olea europaea* occupies a dominant position. Other species in the top canopy include *Cordia africana* Lam. (Arabian teak, Boraginaceae), *Ekebergia capensis* Sparrm. (Cape ash, Meliaceae), *Euphorbia candelabrum*, *Ficus vasta* Forsk. (Moraceae) and other large figs, very few *Juniperus procera*, and scattered clusters of exotic acacias and eucalypts. In the lower story, *Acacia etbaica* Schweinf. (Fabaceae), *Acokanthera schimperi* (A. DC.) Benth. & Hook f. (Arrow poison tree, Apocynaceae), *Bersama abyssinica* Fresen. (Meliaceae), *Calpurnia aurea* (Ait.) Benth. (Wild laburnum, Fabaceae), *Carissa edulis* Croton...
and the species composition of the other bushes generally. In the grazing land (GdeE, GbuW, and GdeW), fewer acacias subsist, climbers fills the rest of the protected area. In the grazing layer composed of grasses and various herbs and (Winter cassia, Caesalpiniaceae). A reasonably dense and erosion.

The LU bordering the church forest to the east (FpaE) was barren land in 1964 because of excessive livestock pressure. It has been closed since 1991 and showed some regeneration on the aerial photograph of 1994. The degraded grazing land (GdeE) is a clear example of continuous degradation: it was occupied by fairly dense bush in 1964, but only few shrubs subsisted in 1994. The large protected area on the western slope (FpaW) was still under dense forest in 1964. It was cleared during the drought and famine of 1984. Similarly to the protected area on the eastern slope, it was closed for cattle in 1990 but had already developed a denser regrowth in 1994. The same holds for FpaeW, except that it was recently enriched with eucalypts. GbuW originated from the same forest complex as the latter two units, was apparently logged in 1984, and has been bushy grazing land since then. GdeW shows a long history of land degradation. It has been degraded and even partially barren land since 1964. Tree and shrub layer of the protected areas (FpaE, FpaW, and FpaeW) mainly consist of regenerating acacias (A. etbaica and to a lesser extent Acacia abyssinica Hochst. ex Benth. [Abyssinian acacia, Fabaceae]) intermixed with relatively dense bushes of Maytenus, Euclea, and Carissa. Other woody species are Dichrostachys cinerea (L.) Wight & Arn. (Sickle bush, Fabaceae), Dodonea angustifolia, Rhus spp., and Senna singueana (Del.) Lock (Winter cassia, Caesalpiniaeae). A reasonably dense ground layer composed of grasses and various herbs and climbers fills the rest of the protected area. In the grazing land (GdeE, GbuW, and GdeW), fewer acacias subsist, and the species composition of the other bushes generally shifts toward Aloe spp. (Aloaceae), Rumex nervosus Vahl (Polygonaceae), and Leucas abyssinica (Benth.) Briq. (Lamiaeae) with increasing soil degradation and decreasing ground cover. In fact, a substantial fraction of these LUs are completely bare soil with calcareous rock fragments, almost certainly attributable to overgrazing and erosion.

Surface-Temperature Models

The seven LUs were characterized by quite distinct surface-temperature profiles which were similar in both seasons (Fig. 2), and all were retained for further analysis. Early-morning temperatures are comparable for all LUTs. During the course of the day, surface temperatures increase progressively and attain a maximum between 12 and 14 hours, depending on LU and LUT. The church forest stays coolest, followed by the protected areas. Grazing land, and in particular degraded grazing land, exhibits a dramatic temperature increase. The quadratic surface-temperature functions provide a very good fit on the field data (except for FpaE in the rainy season $\hat{R}^2 = 0.85$, all $\hat{R}^2 > 0.92$; Table 1).

In the rainy season, all but three land-unit pairs show the highest significant cross-correlation of their modeled temperature functions at zero lag (cross-correlation coefficients: $0.615 \leq r_{cc} \leq 1.000$). The negative lag of FchE compared to that of FpaE ($r_{cc} = 0.534$; lag = 60 minutes) and GbuW ($r_{cc} = 0.573$; lag = 60 minutes) and the negative lag of GdeE compared to that of FpaE ($r_{cc} = 0.589$; lag = 30 minutes) suggest a slight delay of temperature increase of the LUs on the eastern slope (SW aspect) compared to those on the western slope (SE aspect). Surface temperatures on the eastern slope lag 1 hr behind those of LUs on the western slope, where insolation starts earlier because the sun rises in the east. No delays were detected in the dry season.

The instantaneous heat-up-rate functions (Fig.3) show marked differences between land uses. The open area functions (Gde and Gbu) are characterized by high initial heat-up rates and steep slopes, whereas the functions of protected areas (Fpa and Fch) show lower initial heat-up rates and less steep slopes. This indicates that surface temperatures of open areas change more rapidly and that the magnitude of temperature change is higher than that in protected areas. These observations are confirmed in both seasons by Kruskal–Wallis one-way analysis of variance (Table 2). Open areas (grazing land) have a significantly smaller resistance against temperature changes or a lower thermal inertia or TBC than protected areas (and forest). Nevertheless, within seasons, forest, protected area, and grazing land reach their maximum surface temperatures at the same time (Table 2).

Seasonality seems to affect the heat-up rates of forest and two of the three protected areas (not FpaE) only marginally. Open areas, on the other hand, have steeper heat-up-rate functions in the dry season, indicating even more dramatic temperature changes in this season.

Repeated-measures analysis of variance on two TBC indicators, mean TBC at noon ($TBC_{12}$) and mean TBC at $T_{max}$ ($TBC_{vertex}$) (Table 3), confirms the significance of seasonality: TBC is higher in the rainy season. Aspects is marginally significant for $TBC_{12}$ and not significant for $TBC_{vertex}$. Protection status, on the other hand, has a significant effect on both indicators without interaction with aspect. Protected areas have a higher TBC than open grazing land.

There are differences of relative inefficiency of energy digestion between enriched protected area (Fpae), protected area (Fpa), and grazing land (G) ($KW = 4.29; p \leq 0.10$) (Fig. 4). Pairwise comparison showed that only the difference between enriched protected area and grazing land was significant, in both rainy and dry season, and that it was only a marginal difference ($p \leq 0.20$).

These results clearly demonstrate a difference between protected (low heat-up rate and high TBC) and non-protected areas (high heat-up rate and low TBC). Barren,
Degraded grazing land is characterized by the highest heat-up rates, highest maximum temperatures, and highest accumulated heat loads. Protected areas have lower heat-up rates, lower maximum temperatures, and lower accumulated heat loads. It has not been possible, however, to demonstrate significant heat-up rate or TBC differences within the group of protected areas, although the overall ranking suggests that the remnant forest has the highest TBC of all surveyed LUTs, followed by enriched protected areas.

**Discussion**

The ranking suggests that protected areas enriched with *Eucalyptus* have a lower heat-up rate than non-enriched protected areas. Eucalypts might limit the overall rising of the surface temperature because of their high transpiration activity, which is not necessarily to be attributed to a higher transpiration per unit of leaf surface area compared to native trees but rather to their ability to develop a large leaf area very quickly. The annual growth of (young) eucalypts is characterized by a high degree of branching, resulting in quick development of a crown with a large leaf surface area (Lamprecht 1989). This is probably the reason why enriched protected areas have the ability to dissipate solar exergy more efficiently than non-enriched protected areas and thus show a cooler surface temperature. On the other hand, eucalypts are capable of closing their stomata when the atmospheric vapor-pressure deficit is high (Kallarackal & Somen 1997). Hence, the effect of enrichment on the TBC of protected areas will fade away soon in the afternoon during maximum insolation, as can be observed in Figure 2.

Shrubs, herbs, and leaf litter that are associated with forest ecosystems, rather than the trees, play the dominant role in soil protection and water conservation, along with appropriate physical conservation measures. The recovery process of the vegetation following area closure usually starts with the increment in number and cover of grassy species. After some years, shrubs and trees develop and depress the grass component. Results of this study suggest that the TBC quickly responds to area closure. Because the observed protected areas were still in an early

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Figure 2. Observed average surface temperatures in full sunlight (degree centigrade) ± 1 standard deviation in Mai ba’ati (Ethiopia): western and eastern slope in rainy (September 2001) and dry (May 2003) season. Dashed lines are quadratic regression curves (Table 1, Eq. 2). $R^2$ is adjusted $R^2$. $t=0$ is at 07 hours.
succession phase—without dominant tree layer or complete canopy closure—the shrub and herb layers are believed to play a significant role in ecosystem functioning. The understory vegetation is believed to create a forest-like microclimate by controlling the initial decrease of heat-up rate in recovering areas, mainly because of their transpiration potential. The significant higher TBC in the rainy season can therefore most likely be explained by the contribution of the understory transpiration (annual herbs and grasses), which is known to be higher in the wet season (Hutley et al. 2000) and, in this study area, insignificant in the dry season (except in the mature forest). As stated by Joergensen (2001), the developing ecosystem is characterized by an increase of exergy storage and exergy utilization. In a pioneer ecosystem (i.e., recent protected area), the biomass concentration is small compared to a mature system. The structure is simple, and only little energy (exergy) is needed for respiration or growth as they are both to a certain extent proportional to the biomass. The total surface area of the plants is furthermore small, which implies that they are not able to catch and utilize much of the available solar radiation. A more mature ecosystem, for instance, a natural forest or a well-developed protected area, has a much more complex structure and a well-organized trophic network. It contains a high concentration of biomass and information stored over a wide variety of taxa and individuals. The entire structure tries to utilize solar radiation either directly or indirectly, resulting in a high utilization of the solar energy flux. Within the maturing ecosystem, the shift from $r$ strategists (small, short-lived, and numerous organisms on the basis of maximization of population growth; energy and nutrient investment in propagule production) to $K$ strategists (on the basis of filling all the spaces where organisms can live; energy and nutrient

![Figure 3. Instantaneous heat-up rates $T'_i$ (Eq. 3) of land-unit surfaces in Mai ba’ati (Ethiopia) in the rainy season (left) and the dry season (right). Functions are first-derivation functions of modeled quadratic surface-temperature functions.](image)

| Table 2. Effect of land-use groups on instantaneous heat-up rate (Fig. 3; Eq. 3) based on Kruskal–Wallis one-way analysis of variance by ranks for small samples (KW) ($k = 3$, $N = 7$). |
|-----------------|-----------------|-----------------|-----------------|
| **Season**      | **KW (Absolute Slope)** | **KW (Initial Heat-Up Rate)** | **KW (Intercept $t_{\text{inter}}$)** |
| Rainy           | $|2a| = 5.1429^a$   | $b = 4.5714^b$  | $-b/2a = 2.2857^c$ |
| Dry             | $|2a| = 4.5714^b$   | $G > PA^d$      | $-b/2a = 3.1429^c$ |

F, forest (FchE); PA, protected areas (FpaE, FpaW, and FpaeW); G, open grazing land (GdeE, GbuW, and GdeW). Critical values for KW with sample sizes $n_j = 3,3,1$: $^aKW = 5.14$ ($p \leq 0.05$); $^bKW = 4.57$ ($p \leq 0.05$); $^cKW = 4.57$ ($p \leq 0.10$); $^d$ not significant. Significance of contrasts (two-tailed): $^a p \leq 0.15$, $^b p \leq 0.20$. 

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investment in complex organization and specialized organisms) (sensu MacArthur & Wilson 1967; Oldeman 1990), which have a smaller specific surface and, thus, less respiration relative to the biomass, further increases the system’s exergy storage capacities (Odum 1969). Further analysis of more mature protected areas would allow for a detailed study of change in exergy usage as a function of recovery time.

Conclusions
In badly degraded areas such as northern Ethiopia, a serious follow-up of recovering areas is needed to avoid further degradation. Monitoring provides quantitative data for cost–benefit analyses of protected areas and is therefore needed to devise budgetary plans for the limited financial resources available for forest restoration. At the same time, it can offer useful feedback to local communities on their rehabilitation efforts.

This study demonstrates that surface-temperature measurements can be used to monitor protected areas. Average heat-up rates or TBCs can be calculated from surface-temperature measurements in the morning and either at noon or at the maximum temperature ($t_{\text{Tmax}}$). The fixed time method ($TBC_{12}$) requires fewer measurements and is easy to implement but yields less distinctive contrasts and is biased by aspect. The vertex method ($TBC_{\text{vertex}}$) requires a series of measurements around noon to capture the exact maximum temperature and its associated time interval but offers the advantage of canceling out the aspect effect. The decrease of the average heat-up rate a few years after area closure (or an increase of the TBC) is related to the successional stage and complexity of the protected ecosystem. If the average heat-up rate has

| Indicator | Effect Source | F      | p      | Contrast (I–J) a |
|-----------|---------------|--------|--------|------------------|
| $TBC_{12}$ | Within-subject | SEASON | 21.984 | 0.018*           | R > D 7.833* |
|           | Between-subject | ASPECT | 9.121  | 0.057***         | SE > SW 8.306ns |
|           |                | STATUS | 19.149 | 0.022*           | P > O 12.035* |
|           |                | INTERACTION | 2.210   | 0.234ns         |           |
| $TBC_{\text{vertex}}$ | Within-subject | SEASON | 33.181 | 0.010**          | R > D 8.890* |
|          | Between-subject | ASPECT | 1.736  | 0.279ns          | SE > SW 5.251ns |
|          |                | STATUS | 15.013 | 0.030*           | P > O 15.443* |
|          |                | INTERACTION | 0.937   | 0.404ns         |           |

Seasonality is the within-subject factor. *p ≤ 0.05; **p ≤ 0.01; ***p ≤ 0.10; *n*p > 0.10.

*Mean difference between estimated marginal means of the given contrast at $\alpha = 0.05$.

Figure 4. Relative inefficiency of energy digestion of land units in Mai ba’atì (Ethiopia) in the rainy season (left) and the dry season (right) as degree hours emitted more than the reference system FchE. Functions are based on integrated modeled quadratic surface-temperature functions (Eq. 6).
not decreased a few years after closure, the restoration process has possibly failed. The TBC holds a strong signaling function able to detect initial rehabilitation failure and can be used to monitor ecosystem development.

The thermal sensor used in this study is relatively inexpensive and easy to use. It can yield reliable data of land-unit heat-up rates if measurements are taken over the appropriate time intervals, even when operated by comparatively inexperienced people, because botanical knowledge and familiarity with ecological sampling strategies are not a prerequisite. It is therefore strongly recommended that a detailed monitoring strategy for protected areas on the basis of this technology be devised, validated, and finally transferred to the local communities.

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