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

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ABSTRACT

The restoration status of recovering degraded forests 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 traditional vegetation description are often hard or impractical in complex ecosystems. Therefore, an alternative approach is the identification of simple indicators of ecosystem integrity. The use of such indicators can speed up availability of resource inventories and thus contribute to the accelerated implementation of successful rehabilitation practices. Thermal buffer capacity (TBC) of ecosystems has previously been proposed as an overall indicator of ecosystem integrity. In this paper, sequential surface temperature measurements are proposed as a method for TBC assessment of different land use types.

Surface temperatures of 7 land units in Central Tigray (Northern Ethiopia), each with uniform land use type (degraded and bushy grazing land, enriched (planted) and non-enriched restoration area and forest), were measured with a hand-held infrared-

27 thermometer in the rainy and the dry season. Surface temperature models were
28 derived by means of quadratic regression. Cross-correlation functions were
29 calculated for all possible pairs of land unit time series data to compare protected
30 and grazed lands. Instantaneous heat-up rates, average thermal buffer capacity and
31 accumulated heat load were calculated.

32 Time lags between land unit surface temperatures are caused by differences in
33 aspect rather than land use type. Protection status and aspect have a significant
34 effect on the average thermal buffer capacity. Results clearly demonstrate a
35 differentiation between protected (low heat-up rate) and grazed areas (high heat-up
36 rate). Overall ranking suggests that the remnant forest has the highest TBC of all
37 surveyed land use types, followed by the enriched protected area.

38 Results of this study show that thermal buffer capacity quickly responds to protection
39 and can therefore be used to monitor the development of protected areas. It is
40 strongly recommended that a detailed monitoring strategy for protected areas, based
41 on this technology, be devised, validated and finally transferred to the local
42 communities.

43

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

45 **Introduction**

46 Forest degradation and subsequent soil erosion are major environmental problems in
47 many mountain areas (Reasoner et al. 2001), especially in the tropical and
48 subtropical zones. Conversely, forest restoration is considered a powerful instrument
49 for recovery of degraded lands. The factors that affect the rate of restoration include
50 initial site characteristics, management practices and if applicable, plantation design
51 (Wunderle 1997). By comparing their ecosystem characteristics with those of forest
52 remnants, one can assess the current restoration status of recovering areas. This
53 can be done in various ways. Usually, sample plots are laid out in a stratified random
54 design to describe vegetation composition and structure and its relation to
55 environmental variables such as soil characteristics and topology. Results are then
56 compared to a similar dataset of a reference system, most often to what is
57 considered the natural climax vegetation. However, ecosystems in the tropics and
58 subtropics commonly possess a high degree of structural and biological diversity,
59 making comprehensive measurements hard or impractical. Therefore, an alternative
60 approach is the identification of simple indicators of ecosystem integrity. The use of
61 such indicators can speed up availability of resource inventories and thus contribute
62 to the accelerated implementation of successful rehabilitation practices. Many
63 existing ecological indicators are defined as the presence of a taxon or a group of
64 taxa characterized by a distinctive response to a certain set of environmental
65 variables (Burley & Gauld 1994). The measurement of these indicators depends on
66 a high level of knowledge and experience, hindering a wide applicability. According
67 to Bendoricchio and Joergensen (1997), the thermodynamic features of an
68 ecosystem might be more appropriate to capture its overall properties. In this paper,
69 thermal buffer capacity (TBC) is proposed as an overall indicator of ecosystem
70 restoration status, summarizing underlying biotic and abiotic factors of increased

71 control of the biocoenosis over the energy and material flows through the system
72 (Muys et al. 2001, 2003; Wagendorp et al. 2006). Thermal buffer capacity is an
73 indicator related to the thermal response number (TRN) proposed by Luvall and
74 Holbo (1989) to distinguish between land use types with different degrees of integrity.
75 The TRN of ecosystems relates to the amount of energy needed to raise the
76 ecosystem's temperature and can be computed from thermal remote sensing data
77 and measurements of net solar and long wave radiation. Muys et al. (2001)
78 proposed thermal indicators such as surface temperature and TRN to assess human
79 land use impact in the framework of Life Cycle Assessment (LCA) of products from
80 the agriculture and forestry sector. The value of these thermal indicators can be
81 explained by the ecosystem exergy theory. Exergy is defined as energy free of
82 entropy, which consequently is able to do work. Schneider & Kay (1995) formulated
83 the hypothesis that ecosystems with the highest maturity and functional complexity
84 contain the highest exergy level and consume the incoming solar radiation in the
85 most efficient way. As summarized by Wagendorp et al. (2001, 2006), the functional
86 goal of all ecosystems is to maximize dissipation or buffering of exogenic exergy
87 fluxes by maximizing the internal exergy content in the form of biomass, biodiversity
88 and complex trophic networks. As a consequence, the authors aptly stated that
89 natural climax systems are expected to have the highest site-specific exergy level
90 and human impact may decrease ecosystem exergy as a consequence of
91 degradation processes. Similarly, ecosystem restoration may increase the speed at
92 which natural systems reconstruct their exergy level and regain control over
93 radiation, water and nutrient fluxes. Because solar radiation is the main exogenic
94 exergy flow in many terrestrial ecosystems and the thermal features of an ecosystem
95 reveal its ability to dissipate solar exergy, thermal indicators are expected to provide
96 relevant information on the restoration stage of an ecosystem.

97 The use of thermal information is known to be useful for the evaluation of ecosystem
98 physiological activity, functioning and health (Jones 1999; Moran 2000; Samson &
99 Lemeur 2000; Allen et al. 2001). The surface temperature of an ecosystem is
100 believed to give a spatially integrated response of all factors that influence the
101 physiological and physical canopy behavior. Several authors have suggested that
102 undisturbed natural climax systems dissipate solar radiation more effectively, heat up
103 more slowly and consequently show a cooler surface temperature than other
104 systems at the same site (Schneider & Kay 1995; Allen et al. 2001; Wagendorp et al.
105 2001, 2006). The rate of change in surface temperature can be used as a value that
106 reveals how the non-radiative fluxes react to changing radiant energy inputs (Luvall &
107 Holbo 1990). All this suggests that time series measurements of surface
108 temperatures of different land use types can yield a good estimation of their thermal
109 buffering capacity and hence, their restoration status. This multi-temporal approach
110 facilitates a detailed study of the relationship between incoming exergy and its
111 degradation by the ecosystem (Luvall & Holbo 1989, 1990; Allen et al. 2001; Kay et
112 al. 2001).

113 Surface temperatures can be measured with thermal infrared (IR) sensors mounted
114 on platforms ranging from space borne, to airborne to ground measurements (hand-
115 held infrared thermometers). IR-thermometers measure the surface temperature of
116 an object by sensing its emitted, reflected and transmitted thermal infrared radiation
117 (8-14 μm) and translating the information into an integrated temperature reading
118 taking into account the differences in emissivity between surfaces.

119

120 The purpose of this study was 1) to develop a method for thermal buffer capacity
121 assessment of ecosystems based on sequential surface temperature measurements

122 with a hand-held IR-thermometer and 2) to evaluate the thermal buffer capacity of
123 different land use types as a single indicator for forest restoration status.

124

125 **Site Description**

126 The research was carried out in Mai ba'ati (13° 38' N, 39° 13' E; 2200-2350 m above
127 sea level), in the Dega Tembien district of the central highlands of Tigray, Northern-
128 Ethiopia. Soil type and rainfall-temperature relation are the primary factors that
129 determine the pattern of natural vegetation and potentials for agricultural and forest
130 production. The rainfall-temperature relation varies principally with altitude, but
131 recent research pointed out that the slope aspect plays an even more significant role
132 in the spatial distribution of rainfall (Nyssen et al. 2005). Slopes oriented to the east
133 tend to receive more rainfall than those oriented to the west due to rain shadow
134 effects resulting from the prevailing east-west winds during the rainy season. The
135 main soil parent materials in the region are basalt lava and mudflows, sedimentary
136 sandstone and calcareous rocks and lacustrine silified limestone. The soils in the
137 study area are strongly linked to topography and parent material with Vertisols and
138 soils with vertic properties dominating the soilscape in plateau situations wherever
139 basalt is present in the soil profile. In the upper reaches Leptosols are dominant in
140 association with Vertic Cambisols. The footslopes comprise Vertic Calcisols,
141 Calcaric Phaeozems, Vertic Cambisols and Calcaric Regosols. The natural pre-
142 disturbance vegetation of the area is *Podocarpus falcatus* (Thunb.) Mirb. [East-
143 African yellowwood, Podocarpaceae] – *Juniperus procera* Hochst. ex Endl. [East-
144 African pencil cedar; Cupressaceae] forest (Friis 1992; Teketay & Granström 1997),
145 which was cleared at about 500 BC (Darbyshire et al. 2003). In the whole country,
146 only tiny fragments of the original Afromontane forest vegetation remain, usually on
147 inaccessible steep or rocky terrain (Teketay & Granström 1997) or otherwise less

148 accessible land such as sacred church groves. Wilson (1977) summarized the main
149 secondary vegetation types in Central Tigray from various authorities (the most
150 important being Pichi-Sermolli 1957). Three vegetation types presently or potentially
151 occurring in the study area were defined as follows: 1. montane evergreen thicket
152 and scrub (two types: one type with *Euphorbia candelabrum* Tremaut. ex Kotschy
153 [Candelabra tree, Euphorbiaceae] on shallow soils and another type with species of
154 several genera including *Carissa edulis* (Forssk.) Vahl [Natal plum, Apogynaceae],
155 *Euclea racemosa* subsp. *schimperi* (A. DC.) White [Bush guarri, Ebenaceae], *Rhus*
156 *spp.* [Anacardiaceae], *Maytenus senegalensis* (Lam.) Exell. [Red spikethorn,
157 Celastraceae] and *Dodonaea angustifolia* L. f. [Sand olive, Sapindaceae]), 2.
158 montane savanna (usually with *Acacia spp.* [Fabaceae] and *Olea europaea* subsp.
159 *cuspidata* (Wal. ex G. Don) Cif. [African wild olive, Oleaceae] in dominant positions)
160 and 3. montane dry evergreen forest (with *Juniperus procera* and *Olea europaea*).
161 Impoverishment of the increasing highland population and their search for
162 subsistence income has led to a second wave of massive deforestation, site
163 degradation and soil erosion since 1700 CE (Darbyshire et al. 2003). Forest
164 remnants often were overexploited by systematic fuel wood extraction, logging of
165 valuable timber, illegal grazing and unintentional fire. As a result of this massive
166 environmental degradation, recurrent droughts have a stronger negative impact on
167 agricultural production and the environment (i.e., overgrazing, cracking of vertisols,
168 groundwater depletion and increased soil erosion) (Nyssen et al. 2004). Pilot
169 reforestation schemes have been established since 1970. They usually involved
170 terracing of the slopes and planting of (mainly exotic) seedlings grown in nurseries,
171 but were expensive and disturbed the native relict vegetation. Much of the success
172 of the forestation on terraces lies in the natural regrowth of weedy vegetation
173 following exclusion of grazing animals. For that reason, several areas have been

174 closed to livestock since the mid-nineteen eighties. Recently, the Relief Society of
175 Tigray (REST), a rehabilitation NGO, initiated the establishment of such protected
176 areas on a region-wide scale. Although the organization has clearly stated its
177 operational objectives, it does not yet have the scientific or financial capacity to
178 monitor underlying processes and vegetation change in protected areas (Aerts et al.
179 2001). Area closure in the framework of natural forest restoration and soil
180 conservation is a typical example of a major land use change and is therefore
181 considered as a key element in this study.

182

183 **Methods**

184 **Data Collection**

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

190 Contemporary land use was assessed by means of detailed GPS measurements
191 (GeoExplorer III, Trimble Navigation Limited, Sunnyvale CA, USA). The positions of
192 prominent point and linear features such as large trees, boulders, gullies, contour
193 stone bunds and footpaths were recorded for further use as ground control points
194 (GCPs). A 2001 land use map was compiled (Fig. 1b). Information about former
195 land use and land use changes was derived from semi-structured interviews with 15
196 randomly selected resident senior farmers. Former land use maps were derived from
197 aerial photograph interpretation of 1964 and 1994 1:50000 greyscale stereo-couples.
198 The photographs were scanned and integrated in the GIS environment (ArcView GIS
199 3.2a, ESRI, Redlands, CA, USA) after rubber-sheeting (Warp Environment for

200 ArcView GIS, ESRI, Redlands, CA, USA) and geo-referencing (Image Geo-
201 referencing Tools for ArcView GIS, George Raber, USC, Columbia, SC, USA). 1964
202 and 1994 land use was digitized on-screen.

203

204 (Insert Figures 1a and 1b)

205

206 Five contrasting land use types (LUT) were retained for further investigation in this
207 study: a 7.65 ha closed-canopy secondary forest surrounding a Coptic church
208 (further referred to as church forest, Fch), a protected recovering forest area (Fpa), a
209 protected recovering forest area enriched with *Eucalyptus spp.* [Myrtaceae] (Fpae),
210 bushland with grazing and firewood collection (Gbu) and degraded bushland with
211 grazing and firewood collection (Gde). Settlement areas, controlled grazing and
212 browsing areas, farmsteads with cropland, rain-fed cropland and cropland under
213 extensive irrigation were not taken into further consideration.

214 Surface temperatures of 7 land units (LU), blocks with uniform land use type, were
215 measured from two observation points located on a cliff facing the study site from the
216 north (Fig 1b). Four units were located on the western slope (W) with southeast
217 aspect: FpaW (20.40 ha), FpaeW (0.97 ha), GbuW (3.37 ha) and GdeW (26.78 ha).
218 The three other units were situated on the eastern slope (E) with southwest aspect:
219 FchE (7.65 ha), FpaE (2.98 ha) and GdeE (0.57 ha). A hand-held non-contact
220 infrared thermometer (Infrapro 3 WD-35629-20, Oakton Instruments, Vernon Hills, IL,
221 USA) with a temperature range of -32 to 600 °C (accuracy $1/10$ °C $\pm$ 1°C), a spectral
222 response from 8 to 14 μ m and a distance to spot size (D:S) of 30:1 was used. The
223 sensor has the capability to capture 90 % of the outgoing long wave radiation ($L_{\uparrow}$)
224 and yields a surface temperature (T_s) directly in degrees centigrade by using the
225 Stephan-Boltzmann equation (Eq. 1).

$$T_s = \sqrt[4]{\frac{L\uparrow}{\varepsilon \cdot \sigma}} - 273.15 \quad (\text{Equation 1})$$

where T_s = surface temperature in °C

$L\uparrow$ = outgoing long wave radiation

σ = the Stephan-Boltzmann constant

ε = emissivity

227 All measurements were carried out with a fixed assumed infrared emissivity of 0.95,
 228 a standard value for vegetation surfaces [ε = 0.60 for desert surface (Petitcolin et al.
 229 2002); 0.95 for vegetated areas (Nichol 1994), grass (Brutsaert 1982) and leaves
 230 (Jones et al. 2002); 0.98 for closed-canopy forest (Samson & Lemeur 2000)].
 231 For both slopes, the distance from the sensor to the land unit ranged from 320 to 560
 232 m with a maximum elevation difference of 130 m. Accounting for the slope (45°) and
 233 the narrow field of view (FOV=2°) of the sensor, it could be calculated that the spot
 234 size of the sensor ranged from 15 to 26 m², well within the minimal surface area of
 235 the selected land units (5700 m²). The layout of the study area allowed for near-
 236 perpendicular alignment of land surface and sensor, by positioning the sensor at the
 237 eastern end of the cliff when measuring land units on the western slope and vice-
 238 versa. Approximately every half hour, four surface temperatures (each the average
 239 of a 10-second continuous measurement) were recorded for each land unit.
 240 Measurements were carried out at the end of the rainy season in late September
 241 2001 and in the dry season in May 2003 between 7 00 and 16 00 covering the period
 242 of complete insolation of the land units on both slopes. Air temperatures in full shade
 243 during measurements ranged between 17.0 °C (morning) and 25.0 °C (noon) in the
 244 wet season and 19.5 °C and 29.0 °C in the dry season. During periods of partial
 245 shading due to overhead clouds, measurements of land units were delayed for some

minutes (since shading temporarily caused a major surface temperature decrease of the land units). Two 20 × 20 m² sample plots were laid out in each of the 7 land units and their vegetation composition was recorded as presence/absence data.

249

250 **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 land unit) where each row in the dataset represents an observation at a different time, at equally spaced time intervals. Surface temperature measurements in 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 land units. Therefore, second-order polynomial temperature functions were developed from the field data by means of quadratic regression. Surface temperature estimates at equally spaced intervals (half-hourly between 07 00 and 17 00) were derived to create a modelled dataset fit for further analysis (Eq. 2; Table 1).

261

$$T_s = f(t) = at^2 + bt + c \quad \text{(Equation 2)}$$

where T_s surface temperature (°C) and t time (minutes). $t = 0$ at 07 00.

262

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

First derivation functions of the modelled quadratic surface temperature functions were calculated to evaluate instantaneous heat-up rates T' [°C/minute] (Eq. 3).

269

$$T'_i = \frac{dT_{Si}}{dt} = 2at_i + b \quad (\text{Equation 3})$$

270

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

279 As mentioned above, there are reasons to believe that land units with a low thermal
 280 buffer capacity (TBC) will heat up more during a certain time span than land units
 281 with a high TBC. Accordingly, their heat-up rate will be higher. Therefore, the
 282 inverse heat-up rate can be interpreted as an estimator for TBC (Eq. 4) and an
 283 estimation of the average TBC over a time interval of i minutes [minutes/ $^{\circ}\text{C}$] can be
 284 calculated based on temperature measurements (Eq. 5).

$$T\hat{B}C = \frac{dt}{dT_s} = \frac{1}{2at + b} \quad (\text{Equation 4})$$

285

$$\overline{TBC}_i = \frac{\Delta t}{\Delta T_s} = \frac{t_i - t_0}{T_{Si} - T_{S0}} \quad (\text{Equation 5})$$

286

287 Repeated measures analysis of variance was applied to test the effect of aspect and
 288 protection status (open grazing land versus protected area) on mean TBC at noon
 289 ($TBC_{12:00}$) and at $T_{\max}$ (TBC_{vertex}). Season (dry and rainy) was used as within-subject
 290 effect.

Accumulated heat load Q in degree-hours was calculated by integrating under the modelled temperature curves (Eq. 6). Subsequently, relative inefficiency of energy digestion was derived by subtracting the heat-load of the reference system F_{ch} from the heat load of other land units. 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).

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

Results

Land Use Change

Land use change detection showed clear differences in land unit history. Dense forest has continuously occupied the church forest F_{chE} 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* Sparmm. [Cape ash, Meliaceae], *Euphorbia candelabrum*, *Ficus vasta* Forssk. [Moraceae] and other large figs, very few *Juniperus procera* and scattered clusters of exotic acacias and eucalypts. In the lower storey, *Acacia etbaica* Schweinf. [Fabaceae], *Acokanthera schimperi* (A. DC.) Benth. & Hook f. [Arrow poison tree, Apocynaceae], *Bersama abyssinica* Fresen. [Melianthaceae], *Calpurnia aurea* (Ait.) Benth. [Wild laburnum, Fabaceae], *Carissa edulis*, *Croton macrostachys* Hochst. ex Rich. [Euphorbiaceae], *Euclea racemosa*, *Maytenus senegalensis*, *Rhus spp.* and *Ricinus communis* L. [Castor bean,

315 Euphorbiaceae] were recorded among other woody species, including large climbers.
316 Under dense canopy the ground layer is rather sparse. The land unit bordering the
317 church forest to the east (FpaE) was barren land in 1964 due to excessive livestock
318 pressure. It has been protected since 1991 and showed some regeneration on the
319 aerial photo of 1994. The degraded grazing land (GdeE) is a clear example of
320 continuous degradation: it was occupied by fairly dense bush in 1964 but only a few
321 shrubs remained in 1994. The large protected area on the western slope (FpaW)
322 was still under dense forest in 1964. It was cleared during the drought and famine of
323 1984. It was closed to cattle in 1990 and had already developed a denser regrowth
324 in 1994 than the protected area on the eastern slope. The same holds for FpaeW,
325 except that it was recently enriched with eucalypts. GbuW originated from the same
326 forest complex as the latter two units, was apparently logged in 1984 and has been
327 bushy grazing land since then. GdeW shows a long history of land degradation. It
328 has been degraded and even partially barren land since 1964. Tree and shrub layers
329 of the protected areas (FpaE, FpaW and FpaeW) mainly consist of regenerating
330 acacias (*Acacia etbaica* and to a lesser extent *Acacia abyssinica* Hochst. ex Benth.
331 [Abyssinian acacia, Fabaceae]) intermixed with relatively dense bushes of *Maytenus*,
332 *Euclea* and *Carissa*. Other woody species include *Dichrostachys cinerea* (L.) Wight
333 & Arn. [Sickle bush, Fabaceae], *Dodonaea angustifolia*, *Rhus spp.* and *Senna*
334 *singueana* (Del.) Lock [Winter cassia, Caesalpiniaceae]. A reasonably dense ground
335 layer composed of grasses and various herbs and climbers fills the rest of the
336 protected area. In the grazing land (GdeE, GbuW and GdeW), fewer acacias
337 subsist, and the species composition of the other bushes generally shifts towards
338 *Aloe spp.* (Aloaceae), *Rumex nervosus* Vahl [Polygonaceae] and *Leucas abyssinica*
339 (Benth.) Briq. [Lamiaceae] with increasing soil degradation and decreasing ground

cover. In fact, a substantial fraction of these land units is completely bare soil with calcareous rock fragments, almost certainly attributable to overgrazing and erosion.

Surface Temperature Models

The seven land units 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 land use types. During the course of the day, surface temperatures increase progressively and attain a maximum between 12 00 and 14 00, depending on land unit and land use type. 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 to the field data (except for FpaW in the rainy season ($R^2_{\text{adj}} = 0.85$), all $R^2_{\text{adj}} > 0.92$; Table 1).

(Insert Figure 2; multi-part full page landscape; 4 graphs)

(Insert Table 1)

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

366 The instantaneous heat-up rate functions (Fig. 3) show marked differences between
367 land uses. The grazed area functions (Gde, Gbu) are characterized by high initial
368 heat-up rates and steep slopes, whereas the functions of protected areas (Fpa, Fch)
369 show lower initial heat-up rates and less steep slopes. This indicates that surface
370 temperatures of grazed areas change more rapidly and that the magnitude of
371 temperature change is higher than in protected areas. These observations are
372 confirmed in both seasons by Kruskal-Wallis one-way analysis of variance (Table 2).
373 Unprotected areas (grazing land) have, in other words, a significantly smaller
374 resistance against temperature changes or a lower thermal inertia or TBC than
375 protected areas (and forest). Nevertheless, the intercepts or the times when
376 surfaces reach their maximum temperatures do not differ significantly between land
377 uses within seasons (Table 2).

378 Seasonality seems to affect the heat-up rates of forest and protected areas only
379 marginally. Grazed areas on the other hand have steeper heat-up rate functions in
380 the dry season, indicating even more dramatic temperature changes in this season.

381

382 (Insert Figure 3; multi-part left/right; 2 graphs)

383 (Insert Table 2)

384

385 Repeated measures analysis of variance on two TBC indicators, mean TBC at noon
386 ($TBC_{12:00}$) and mean TBC at T_{max} (TBC_{vertex}) (Table 3), confirms the significance of
387 seasonality: thermal buffer capacity is higher in the rainy season. Aspect is
388 marginally significant for $TBC_{12:00}$ and not significant for TBC_{vertex} . Protection status
389 on the other hand has a significant effect on both indicators without interaction with
390 aspect. Protected areas have a higher TBC than grazing land.

391

392 (Insert Table 3)

393

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

399

400 (Insert Figure 4; multi-part left/right;2 graphs)

401

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

411

412 **Discussion**

413 The ranking suggests that protected areas enriched with *Eucalyptus* have a lower
414 heat-up rate than non-enriched protected areas. Eucalypts might limit the overall
415 rising of the surface temperature due to their high transpiration activity, which is not
416 necessarily attributed to a higher transpiration per unit of leaf surface area compared
417 to native trees, but rather to their ability to develop a large leaf area very quickly. The

418 annual growth of (young) eucalypts is characterized by a high degree of branching,
419 resulting in quick development of a crown with a large leaf surface area (Lamprecht
420 1989). This is probably the reason why enriched protected areas have the ability to
421 dissipate solar exergy more efficiently than non-enriched protected areas and thus
422 show a cooler surface temperature. On the other hand, eucalypts are capable of
423 closing their stomata when the atmospheric vapor pressure deficit is high (Kallarackal
424 & Somen 1997). Hence, the effect of enrichment on the TBC of protected areas
425 diminishes in the afternoon during maximum insolation. Enrichment with native trees
426 has not been done in the study area, but would be expected to create a temperature
427 profile more similar to the church forest in later stages when the trees have
428 developed sufficiently.

429 Shrubs, herbs and leaf litter that are associated with forest ecosystems, rather than
430 the trees, play the dominant role in soil protection and water conservation, along with
431 appropriate physical conservation measures. The recovery process of the vegetation
432 following area closure usually starts with the increment in number and cover of
433 grassy species. After some years shrubs and trees develop and depress the grass
434 component. Results of this study suggest that the thermal buffer capacity quickly
435 responds to area closure. Since the observed protected areas were still in an early
436 succession phase – without dominant tree layer or complete canopy closure – the
437 shrub and herb layers are believed to play a significant role in ecosystem functioning.
438 The understorey vegetation is thought to create a forest-like microclimate by
439 controlling the initial decrease of heat-up rate in recovering areas, mainly as a
440 consequence of their transpiration potential. The significant higher thermal buffer
441 capacity in the rainy season can therefore most likely be explained by the
442 contribution of the understorey transpiration (annual herbs and grasses), which is
443 known to be higher in the wet season (Hutley et al. 2000) and, in this study area,

444 insignificant in the dry season (except in the mature forest). As stated by Joergensen
445 (2001) the developing ecosystem is characterized by an increase of exergy storage
446 and exergy utilization. In a pioneer ecosystem (i.e. recently protected area) the
447 biomass concentration is small compared to a mature system. The structure is
448 simple and only little energy (exergy) is needed for respiration or growth since they
449 are both, to a certain extent, proportional to the biomass. The total surface area of
450 the plants is furthermore small, which implies that they are not able to catch and
451 utilize much of the available solar radiation. A more mature ecosystem, for instance
452 a natural forest or a well-developed protected area, has a much more complex
453 structure and a well-organized trophic network. It contains a high concentration of
454 biomass and information stored over a wide variety of taxa and individuals. The
455 entire structure tries to utilize solar radiation, either directly or indirectly, resulting in a
456 high utilization of the solar energy flux. Within the maturing ecosystem, the shift from
457 r strategists (small, short-lived and numerous organisms based upon maximization of
458 population growth; energy and nutrient investment in propagule production) to K
459 strategists (based upon filling all the spaces where organisms can live; energy and
460 nutrient investment in complex organization and specialized organisms) (sensu
461 MacArthur & Wilson 1967; Oldeman 1990), which have a smaller specific surface
462 and thus less respiration relative to the biomass, further increases the system's
463 exergy storage capacities (Odum 1969). Further analysis of more mature protected
464 areas would allow for a detailed study of change in exergy usage as a function of
465 recovery time.

466

467 **Conclusions**

468 In badly degraded areas such as Northern Ethiopia, a serious follow-up of recovering
469 areas is needed to avoid further degradation. Monitoring provides quantitative data

470 for cost/benefit analyses of protected areas, and is as such needed to devise
471 budgetary plans for the limited financial resources available for forest restoration. At
472 the same time, it can offer useful feedback to local communities on their restoration
473 efforts.

474 This study demonstrates that surface temperature measurements can be used to
475 monitor protected areas. Average heat-up rates or thermal buffer capacities can be
476 calculated from surface temperature measurements in the morning and either at
477 noon or at the maximum temperature (t_{Tmax}). The fixed time method ($TBC_{12:00}$)
478 requires fewer measurements and is easy to implement but yields less distinctive
479 contrasts and is biased by aspect. The vertex method (TBC_{vertex}) requires a series of
480 measurements around noon to capture the exact maximum temperature and its
481 associated time interval but offers the advantage of cancelling out the aspect effect.
482 The decrease of the average heat-up rate a few years after area closure (or an
483 increase of the TBC) is related with the successional stage and complexity of the
484 protected ecosystem. If the average heat-up rate has not decreased a few years
485 after closure, the restoration process has possibly failed. In other words, thermal
486 buffer capacity holds a strong signalling function able to detect initial rehabilitation
487 failure and can be used to monitor ecosystem development.

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

495

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503

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Table 1. Parameters of the quadratic surface temperature models for Mai ba'ati (Ethiopia) (Eq. 2), F-value and adjusted R².

Season	Aspect	Land unit ¹	$a (\times 10^{-5})$	$b (\times 10^{-2})$	c	F	R ² _{adj}
Rainy	SW	RFchE	-4.569	5.000	11.45	636.44***	0.9556
		RFpaE	-6.675	5.930	12.98	610.14***	0.9538
		RGdeE	-8.421	7.797	11.61	940.67***	0.9696
	SE	RFpaW	-6.903	4.313	17.63	155.54***	0.8489
		RFpaeW	-5.551	4.081	15.77	313.17***	0.9190
		RGbuW	-10.90	6.956	16.48	394.70***	0.9347
		RGdeW	-13.40	9.585	14.05	1621.4***	0.9833
Dry	SW	DFchE	-6.290	5.966	12.92	830.46***	0.9646
		DFpaE	-9.895	8.814	10.76	781.76***	0.9612
		DGdeE	-14.60	12.41	8.568	887.31***	0.9657
	SE	DFpaW	-9.562	6.598	17.58	678.58***	0.9693
		DFpaeW	-5.780	4.917	17.47	381.70***	0.9465
		DGbuW	-13.70	9.169	17.81	810.24***	0.9741
		DGdeW	-15.40	11.35	15.66	908.38***	0.9769

*** F-test $p < 0.0001$

¹ Fch: church forest; Fpa: protected area; Fpae: enriched protected area; Gbu: bushy grazing land; Gde: degraded grazing land. R/D and E/W refer to season and aspect. See Methods for details.

Table 2. Effect of land use groups on instantaneous heat-up rate (Fig. 3; Eq. 3) based on Kruskal-Wallis (KW) one-way analysis of variance by ranks for small samples ($k = 3$, $N = 7$)[†] in the rainy and dry seasons.

	KW		
	KW(Absolute slope)	KW(Initial heat-up rate)	KW(Intercept $t_{(T_{max})}$)
Season	2a	b	-b/2a
Rainy	5.1429*	4.5714 ^(*)	2.2857 ^{ns}
	G > F ^(x)	G > PA ^(x)	
Dry	4.5714 ^(*)	4.5714 ^(*)	3.1429 ^{ns}
	G > PA ⁽⁺⁾	G > PA ⁽⁺⁾	

[†] Groups: Forest (F): FchE; protected areas (PA): FpaE, FpaW, FpaeW; open grazing land (G): GdeE, GbuW, GdeW. See Methods for abbreviations.

Critical values for KW with sample sizes $n_j = 3, 3, 1$: ^(*) KW = 4.57 ($p \leq 0.10$); * KW = 5.14 ($p \leq 0.05$); ^{ns} not significant. Significance of contrasts (2-tailed): ^(x) $p \leq 0.15$ and ⁽⁺⁾ $p \leq 0.20$

Table 3. Effect of season, aspect and protection status on two thermal buffer capacity (TBC) indicators based on repeated measures analysis of variance (n = 7). Seasonality is the within-subject factor.

Indicator	Effect	Source	F	p [†]	Contrast [*]	(I-J) [‡]
$\overline{TBC}_{12:00}$	within-subject	SEASON	21.984	0.018*	R>D	7.833*
	between-subject	ASPECT	9.121	0.057 ^(*)	SE>SW	8.306 ^{ns}
		STATUS	19.149	0.022*	P>O	12.035*
		INTERACTION	2.210	0.234 ^{ns}		
$\overline{TBC}_{\text{vertex}}$	within-subject	SEASON	33.181	0.010**	R>D	8.890*
	between-subject	ASPECT	1.736	0.279 ^{ns}	SE>SW	5.251 ^{ns}
		STATUS	15.013	0.030*	P>O	15.443*
		INTERACTION	0.937	0.404 ^{ns}		

[†] ** p ≤ 0.01; * p ≤ 0.05; ^(*) p ≤ 0.10; ^{ns} p > 0.10; [‡] Mean difference between estimated marginal means of the given contrast at α = 0.05.

* R/D: rainy and dry seasons; SE/SW: southeast and southwest aspect; P/O: protected and unprotected land.

Figure 1. a. Aerial photograph of Mai ba'ati (2001). b. Mai ba'ati land use (2001): church forest (Fch); protected area (Fpa); protected area enriched with eucalypts (Fpae); controlled grazing and browsing (Gco); bush land with grazing and firewood collection (Gbu); degraded grazing land with firewood collection (Gde); rain-fed cultivation (Crf) and farmsteads with cropland (Cfs). The 10-meter contours are indicative (based on interpolation of ground control point heights).

Figure 2. Observed average surface temperatures in full sunlight ($^{\circ}\text{C}$) $\pm$ 1SD in Mai ba'ati (Ethiopia): western and eastern slope in rainy (09/2001) and dry (05/2003) season. Dashed lines are quadratic regression curves (Table 1, Eq. 2). R^2 is adjusted R^2 . $t=0$ is at 07 00 am. R = rainy season, D = dry season. See Methods for site abbreviations.

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 modelled quadratic surface temperature functions. R = rainy season, D = dry season. See Methods for site abbreviations.

Figure 4. Relative inefficiency of energy dissipation of land units in Mai ba'ati (Ethiopia) in the rainy season (left) and the dry season (right) as degree-hours emitted more than the reference system church forest (FchE). Functions are based on integrated modelled quadratic surface temperature functions (Eq. 6). R = rainy season, D = dry season. See Methods for site abbreviations.

Figures

Fig. 1a

Fig. 1b

Fig. 2

Fig. 3

Fig. 4