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Shortwave Radiation Absorption into a Grassland-Pasture Competition Model

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Abstract. A central objective of the present study is to cover the lack of information about growing mechanisms of an invasive and toxic species, the southern bracken (*Pteridium arachnoideum*), over cultivated pasture. One of the main hypotheses, which explain the growth advantage of bracken, is related to the absorption of solar radiation. This was the starting point to investigate the competition between bracken and the most common pasture (*Setaria sphacelata*). Using reflectance spectroscopy and canopy analysis techniques a set of parameters was obtained as input to a mathematical scheme. This scheme includes a state-of-art canopy transfer solution, with that absorption of shortwave radiation was calculated for both species under different illumination conditions. Potentially, bracken absorbs an average of 1.2 $MJ.m^{-2}.day^{-1}$ more than *Setaria* in nearly 40% of year. *Setaria* absorbs 0.2 $MJ.m^{-2}.day^{-1}$ more than bracken in the rest of the year. Cloudiness, which changes the properties of incident radiation, can be seen as a driving factor in the context of climate changes. This results show the feasibility of a model, driven by field measurements, to investigate competition for light of separated vegetation traits. In the future a spatial component shall be included, as well as other limiting factors to vegetation growth, approximating the model to the investigation on a land cover basis.

Palavras-chave: shortwave radiation absorption, reflectance spectroscopy, canopy analyser, balloon photography, absorção de radiação de ondas curtas, espectroscopia, análise de copa, fotografia com balão.

1. Introduction

Grasslands cover circa 22% of global land and are generally related to a broad range of annual mean temperature and annual precipitation. Grasslands occur naturally following surface adaptation to extreme climates, like those of high elevations. From a biophysical point of view this process involves the energy balance and solar radiation storage into thermal or biochemical energy. On extreme weather environments plants toughly compete by controlling water and heat losses. This process arises gradually and not constant and involves an intricate system. Such investigation can be applied not only to the natural occurrence but also to understand grasslands as a direct resource or as a secondary succession after land use. In this work we present a vegetation-atmosphere model under construction. At the current stage responses to atmospheric inputs are being investigated. Developing the model, we make use of concepts and procedures from dynamic global vegetation models to calculate solar radiation absorption under different illumination conditions. The result is a radiation module, used to calculate potential inputs to vegetation growth.

A non-spatial approach was firstly considered to depict competitive potentials from two grassland species: the grass *Setaria* (*Setaria sphacelata*), a widespread advantageous pasture species, and the southern Bracken fern (*Pteridium arachnoideum*), a high competitive weed. These species represent pastorization issues on mountainous regions. The current study is part of the multidisciplinary ecological research ‘Biodiversity and Sustainable Management of a Megadiverse Mountain Ecosystem in South Ecuador’. Current progresses are being reported at the website of the Research Unit 816 <http://www.tropicalmountainforest.org/>. A first collection of works was recently published in Beck et al. (2008), which gives a broad context and findings related to the research site.

2. Study Area

Supporting the presented subject, investigations have been carried out since 1998 at the ecological research station (*Estación ecológica de San Francisco*, ECSF) on the eastern Andes of south Ecuador. The research station is located at latitude 3°58’S, longitude 79°5’W, and altitude 1.860 meters above sea level). On the eastern Andes a perhumid climate dominates, mainly due to atmospheric fluxes from Amazon. This frequent cloudiness, as reported by Bendix et al., (2006) controls the radiation regime from these high elevated areas. Since 2007 experimental plots 10x10 m^2 were established to monitor vegetation growth after clearing by slash and burn. A meteorological station was mounted near this site at an altitude of 2120 m a.s.l. and data are logged each five minutes since November 2007. A set of radiation data used as input in the model is summarized in the section 5. A brief pictorial description is shown in section 4.3.

3. Radiation Module

Absorption of solar radiation involves its transfer and scattering within the canopy. As assumptions we used the two-stream approximation, considering single scattering, uniform leaf orientation and shaded and sunlit leaves (two-big-leaf approach). A complete description of the radiation scheme can be found in the work of Dai et al. (2003). Important to note is that the dimension for penetration of light within the canopy is the Leaf Area Index. This can be leveraged by the Leaf Angle to a geometric relation to the illumination purposes. Leaf Area and Leaf Angle are parameters to be quantified on field, as presented in sections 4.2 and 4.3. Like for a larger scale purposes vegetation cover is summarized into averaged traits or plant functional types. This radiation scheme has been implemented to application on a global scale, making use of reanalysis and remote sensing data (Oleson et al. 2004). Radiation inputs should be given divided into its components direct and diffuse. To do that an empirical relation can be used to decompose the global radiations (Erbs et al. 1982).

4. Field Measurements

To better evaluate climate effects over bracken and *Setaria* development a complete meteorological station delivers data from the experimental plots on a 5-minute temporal resolution since 2007. Although only global radiation data are analysed here, it is a complete meteorological station and remotely managed. Wireless LAN Connection (2.4 GHz, 802.11f, speed 54 Mbit/s), with 18db gain antenna, allows remote access to data transfer and software manipulation. A network structure of other three meteorological stations at different elevations delivers the data for other present investigations on mountain gradient in South Ecuador. Occasionally the operation of the devices had been interrupted, also due to maintenance procedures, but gaps do not hinder independent month analysis. Further inter-comparison between stations can provide interpolation for short time scale investigations.

4.1. Optical Parameters of Vegetation

Optical spectroscopy from the considered species was carried out leading to averaged spectral signatures, or the plant optical traits. Spectral signatures were measured using a field spectrometer mounted on a fixed base. Leaves were collected and inserted in a wooden frame over a black painted area of one square meter. The same was proceeded with to soil samples. The instrument (Tec5 HandySpec Field 14) is a product from the company Tec5 <www.tec5.com> and consist of two sensors (MMS and PGS) for acquisition from different spectral ranges. The MMS, or Monolithic Miniature Spectrometer, provides instantaneous spectrum records using one diode array. It is a controlled semi-conductor photodiode (NMOS) with high sensibility on visible and near infra red (310 -1 100 nm, dl = 3.3 nm). For this sensor, a specific grating correction is embedded, which allows adjusted focal curve of non-polarized light to the detector. The Plane Grain Spectrometer (PGS) contains also a detector array of a sensible material (Indium Gallium Arsenide). It corresponds to the infra red sensor, since its spectral range extends from 960 to 1 690 nm (dl = 1.5 nm). Theses sensors runs simultaneously in two channels provided by an optical multiplexer.

After three collecting sessions, transmittance and absorption were analysed to the visible and near infra red area of the spectrum. However, in this work, we make use of the properties from the visible range. Visible optical properties control the potential absorption of the incident PAR radiation (300 – 700 nm) normal to the leaves. These data are presented in Figure 1. Notably is a lower reflectance and transmittance found to Bracken in the visible range (reflectance = 7.4, transmittance = 3.7) in comparison to Setaria traits (reflectance = 11.7; transmittance =. 1.5).

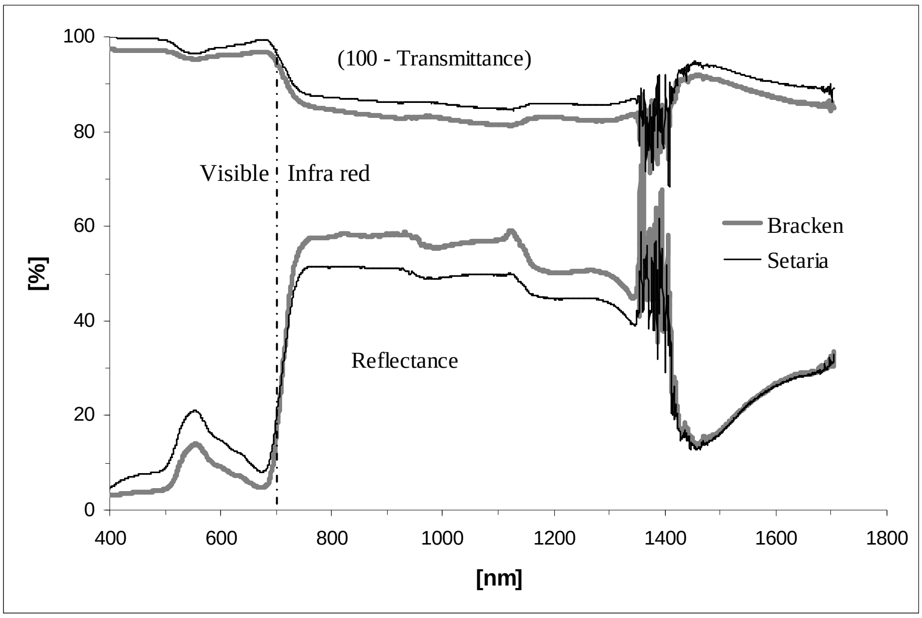

Figure 1. Spectral signatures of fresh leaves of Bracken and *Setaria*.

4.2. Structural Parameters of Vegetation

Two parameters are considered in the context of the applied model (described in section 3) for the canopy radiation transfer: the first parameter is the Leaf Area Index, or LAI, defined as the one-sided leaf area on the plant canopy for each unit (square meter) of ground. For monitoring purposes, which requires repeatability, indirect measurements of the leaf area index were adopted. This results in underestimated values, because of clumping effects, but not so pronounced in this case, in which woody parts are absent. So, the LAI was measured with a Li-cor LAI-2000 plant canopy analyser. Embedded in this instrument is fish eye sensor sensible to the blue light (320 – 490 nm) to measure radiation above and below the canopy. LAI results from the transmission measurements related to foliage density estimated at five different angles from the semi-hemisphere under the canopy.

The second parameter is the Leaf Angle parameter, which is more complex due to braches arrangement and unequal angles from the ground to the top of plant canopy. Considering a mean value used to represent plant traits and neglecting azimuth angles, we use the mean tilt angle as obtained from the LAI-2000 plant canopy analyser. It is in good agreement with the assumptions made for whole vegetation units, where simplified concepts are used to efficiently model radiation absorption and flux exchanges over large areas on a grid-cell based approach.

Averages of 18 field measurements resulted in Leaf Area Index of 2.40 and 2.94 (m^2/m^2) and Leaf Angle Distribution of -0.37 and 0.48 (-1, vertical to 1, horizontal) to *Setaria* and Bracken respectively. It means a slightly larger leaf area with predominantly horizontal leaves from Bracken. *Setaria* has more vertical leaves and a higher density near the ground. Bracken has an opened canopy, which forms a little understory environment.

4.3. Balloon Photography

Two balloon flights were carried out on mid September 2008 to take low altitude aerial photographs. The sky was partially covered, sunny on the morning, with low winds predominating during the day. It was reported as a climatic window, succeeding and followed by rainy days, very common on the eastern Andes in Ecuador. The thin air over 2 130 m a.s.l was crucial to a first approach with a 500g weight camera, which suffered consecutive crashes after starting. A lighter 125g weight camera was then adapted in the support frame, allowing a successful flight. We use a helium balloon with a capacity of 3.2 m^3 to lift the camera up to 40 m above ground. The balloon was stabilized to record the plots over a sky line at circa 10m height to take high definition pictures.

The resulting pictures present details from leaves. Perspective effects were corrected using stitching techniques. It consists of control points selection and the recalculation of the field of view over a new planar projection. A final mosaic of these pictures is presented in Figure 2. Granulation (in dpi) was later converted to centimetres by means of visual inspection to achieve the best thresholds based on ground metric marks. The fine resolution achieved required a precise topographic measurement to the geo-rectification. This was done using a metric tape and an experimental ultrasonic measuring device. In addition a handheld GPS was used to give the orientation necessary to register the picture. The balloon photography technique will be used to document and measure the spatial distribution and fraction of cover during a succession after fire.

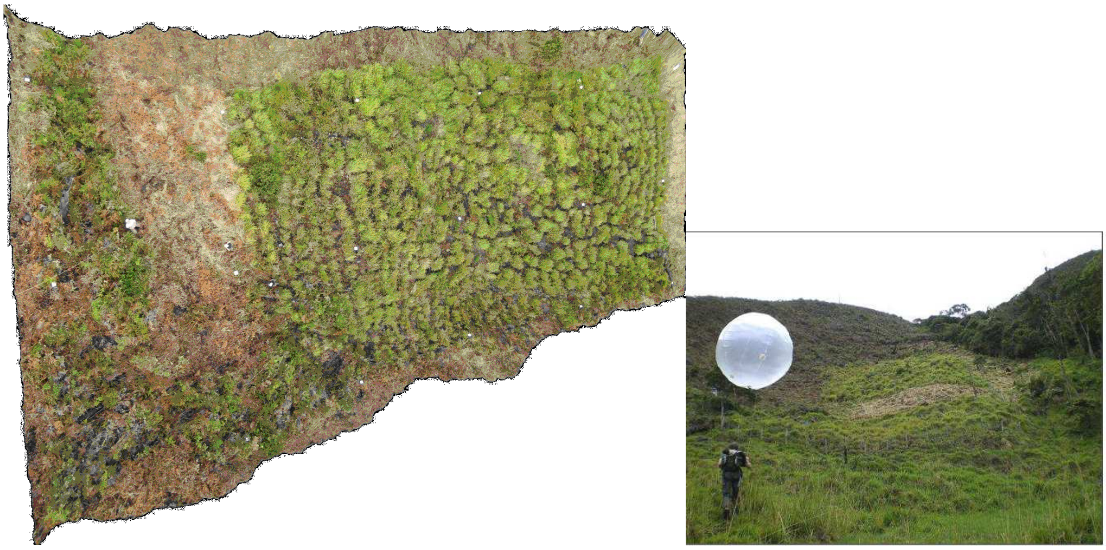

Figure 2. Resulting mosaic from Balloon Photography and view from experimental site at day of flight.

5. Results and Discussion

The interception of solar photosynthetic radiation (PAR) was analyzed using parameters from the canopy model (as shown in section 4.1 and 4.2). A sensibility analysis is not presented here, but is part of the current research and publication. In terms of absorption and considering annual hourly means, *Setaria* yields are around 4.5 $MJ.m^{-2}.day^{-1}$, 0.3 more than bracken. Cloudy days are slightly favourable to *Setaria* which absorbs 2.1 $MJ.m^{-2}.day^{-1}$, 0.2 more than bracken. Clear days are very favourable to bracken which absorbs 8.5 $MJ.m^{-2}.day^{-1}$, 1.2 more than *Setaria*. Monthly hourly means give us a seasonal distribution of absorption, which is presented in Figures 3 to 5. Notable is a stronger correlation between the absorbed radiation from *Setaria* (Figure 5, left) and the diffuse component of radiation (Figure 3, right) in comparison with bracken. By bracken canopies occurs the opposite with short spots of higher absorption from direct radiation (Figure 4, middle), which shows strong correlation to the direct radiation.

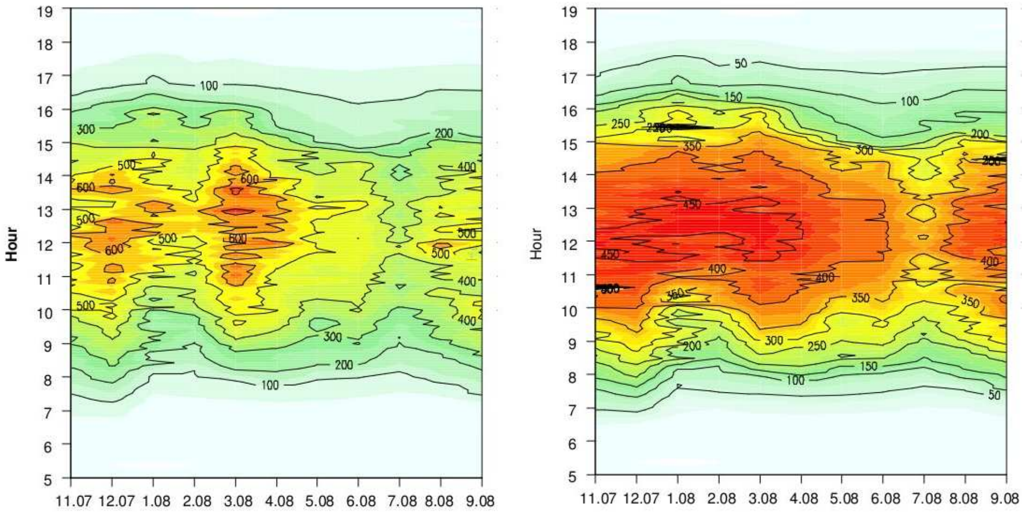

Figure 3. Direct (right) and diffuse (left) radiation measured at the experimental plots.

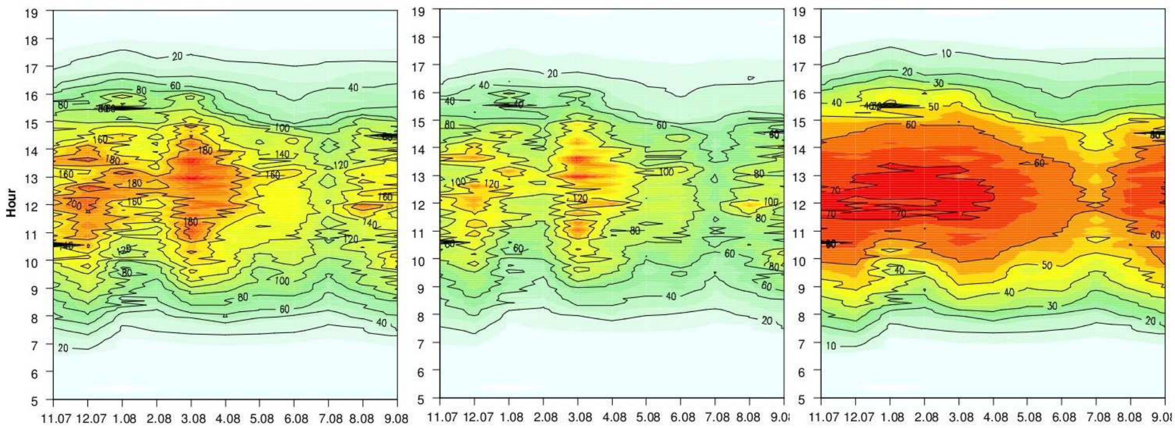

Figure 4. Total radiation absorbed by bracken (left) and the absorbed from the direct (middle) and diffuse radiation (right).

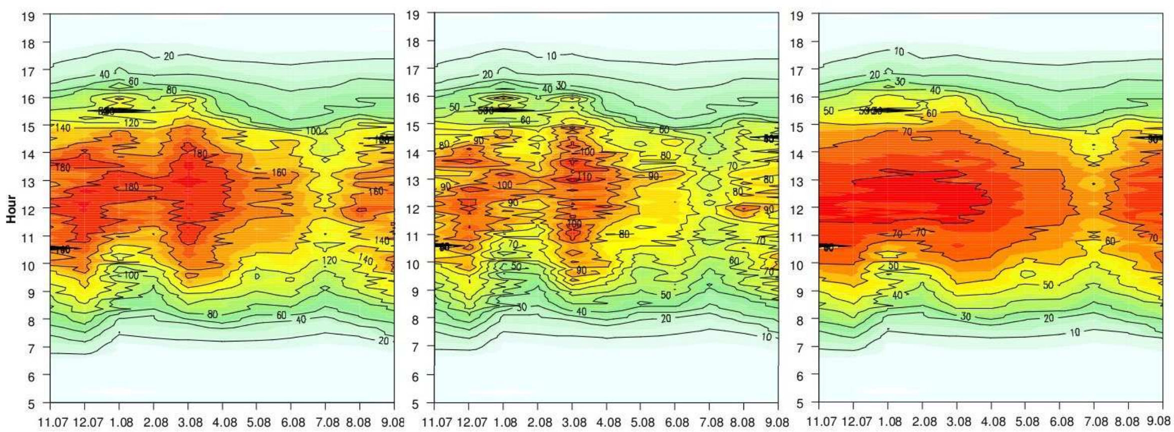

Figure 5. Total radiation absorbed by *Setaria* (left) and the absorbed from the direct (middle) and diffuse radiation (right).

The average daily incident radiation was 26.7 $MJ.m^{-2}$ (maximum of 52.3 $MJ.m^{-2}.day^{-1}$, minimum 4 $MJ.m^{-2}.day^{-1}$) for the first three seasons of observation (Nov 2007 to May 2008). With exception of a short dry season occurring between September and November, clouds are quite constant over the year and more frequent on higher slopes. Considering the observed values, 55% of the incoming global radiation was under the mean value, which means higher diffuse radiation. This leads to an averaged absorption of 30.2% of the incoming radiation from Bracken, against 32.4% from *Setaria*. This slight advantage for *Setaria* is outperformed by bracken on sunny days and the surplus of absorbed radiation by bracken achieves 1.2 $MJ.m^{-2}.day^{-1}$ throughout the year against the absorbed radiation by *Setaria*. This is much more than the 0.2 $MJ.m^{-2}.day^{-1}$ more absorbed by *Setaria* on mostly (60%) of days.

Further, if a moderate change occurs in the next decades, as reported by the IPCC (A1B scenario, in Solomon et al., 2007), a reduction of 4% in cloud is expected for south Ecuador. With the increase of direct radiation, favourable conditions will become more frequent to bracken. Certainly, it emphasizes the necessity to take different measures and avoid the abandonment of the areas invaded by bracken. Examples can be found on cultivation techniques based on atmospheric inputs, or atmospheric circulation near the surface. More than support the sustainable management of pastures, it shall diminish the gain of forested areas.

6. Conclusion

A numerical scheme was developed to estimate light absorption by two competing plant species. The competition model may achieve large space dimensions, not considered yet, but visible in field. For now it was important to reveal that the competition for light between bracken and *Setaria* can be investigated using a modelling approach. Spectroscopy and canopy analyser equipment was successfully applied as parameterization procedures to initialize the model. Also the potential use of the installed network of meteorological stations can be emphasized. It shall be used as ground validation to atmospheric parameters, or control for vegetation growth, on a larger spatial scale. Future works are planned to enhance the model by including not only the spatial dimension, but also other limiting factors for biomass production, since they form a more complete basis for competition. The balloon photography, which was successfully started, may be seen as a useful tool to monitor plant cover at this site. Further it shall be necessary to understand biomass to plant cover relations. The idea behind is to compare simulated biomass and plant cover with observed values on the experimental plots.

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