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ON THE RED TO FAR-RED RATIOS OF LIGHT PROPAGATED BY SAND-TEXTURED SOILS

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ABSTRACT

The expansion of landscapes formed by sand-textured soils is increasing due to aridity and desertification processes elicited by human activities and climate change. Vegetation restoration initiatives are instrumental to mitigate this trend. These initiatives involve the combined use of satellite, ground-based and *in silico* data in the detection and management of abiotic stress factors affecting seed germination and plant development in these regions. These photobiological phenomena, in turn, are often mediated by the red to far-red ratios of impinging light. In this paper, we examine the key differences between the red to far-red ratios of light propagated by sand-textured soils characterized by either a dominant presence of hematite or goethite (limonite), the mineral impurities largely responsible for their colors. Moreover, we also address the sensitivity of these ratios to different water distribution patterns: present in these soils' pore space or forming films around their constituent grains. By strengthening the current understanding about the interconnected effects of these abiotic factors, our findings are expected to contribute to the development of new cost-effective technologies for the monitoring (*in situ* and remotely) of sandy landscapes and the restoration of vegetation in these regions.

Index Terms— sand, hyperspectral responses, aridity.

1. INTRODUCTION

More than one third of the Earth's land surface is covered by sand-textured soils, commonly referred to as natural sands. They tend to become even more prevalent as aridity and desertification processes elicited by human activities and climate change continue to take place [1]. One of the main strategies employed to address this situation, detrimental to a wide range of ecosystems, involves the establishment of new populations of stress-adaptable plants in the affected areas [2].

It has been observed that the more extreme the environment, the more efficient the mechanisms evolved by a plant in its overall adaptation to adverse growing conditions [3]. Accordingly, plants capable of developing in perennial arid landscapes have a key role in these vegetation restoration efforts [2]. The success of these initiatives, however, is tied to the effective detection and management of stress factors affecting these plants' life cycle. To achieve that, the combined use of satellite, ground-based and *in silico* (computational) data becomes instrumental.

A wide range of plant species are characterized by the presence of proteins forming pigments that regulate various physiological and developmental responses. These include, for instance, seed germination, chloroplast movement and shade avoidance. During exposure to light, these proteins (phytochromes) are constantly transformed from a red light absorbing conformation to a far-red light absorbing conformation, and back. Changes in the ratios of red to far-red impinging light can alter this balance [4, 5].

In this paper, we evaluate the red to far-red ratios of light propagated by representative samples of sand-textured soils characterized by a dominant presence of either hematite or goethite (limonite), iron oxides with strong light attenuation properties in the visible (photosynthetic) spectral domain. Our investigation was carried out through controlled *in silico* experiments performed using a first-principles simulation framework supported by measured data. Since light propagation by sand-textured soils can be significantly affected by the presence of water, the effects of distinct water content and distribution patterns on the samples' red to far-red ratios are also systematically examined in our investigation.

The presence of water in a soil sample is usually quantified in terms of its degree of water saturation (S) [6], which can be associated with the probability of light encountering water while traversing the sample's pore space. There are also situations in which the grains of dry layers of soil, albeit immersed in a pore space filled with air, may be encapsulated by water films. For instance, this may happen after the bulk of water in the pore space has been either drained via gravity or partially evaporated, leaving only the water films created by surface tension between the water and the grains [7]. Such situations are also accounted for in our *in silico* experiments.

Our investigation aims to strengthen the current understanding about the interconnected effects of the sand-textured soils' mineralogy and water presence patterns on their red to far-red ratios. Moreover, in the analysis of our findings, we also discuss their implications for photobiological phenomena, notably seed germination and plant growth, associated with the restoration of vegetation in arid landscapes.

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2. MATERIALS AND METHODS

For the purposes of our investigation, we selected samples from natural sand deposits with distinct mineralogical characteristics, namely a red (hematite rich) Australian dune and a yellowish (goethite-rich) Californian outcrop. They correspond to samples used in actual sand reflectance measurements [8], which we employed as baseline references for our *in silico* experiments.

In the characterization of the selected samples, we considered quartz as their core material and kaolinite as their grains' coating matrix. In addition, we assigned mean values for their porosity (0.425), grain roundness (0.482) and grain sphericity (0.798) [6]. The remaining parameter values used in their characterization, which are presented in Table 1, were also chosen from physically valid ranges reported in the literature [6]. Note that the percentages of the sand-sized and silt-sized particles depicted in Table 1 are employed to compute the dimensions of the samples' grains using a particle size distribution provided by Shirazi et al. [9].

Table 1. Parameter values used to characterize the sand-textured soil samples selected for this investigation. The texture of the samples is described by the percentages (%) of sand (s_a) and silt (s_i). The particle type distributions considered in the simulations are given in terms of the percentages (%) of pure (μ_p), mixed (μ_m) and coated (μ_c) grains. The parameter r_{hg} corresponds to the ratio between the mass fraction of hematite to ϑ_{hg} (the total mass fraction of hematite and goethite).

Samples	s_a	s_i	μ_p	μ_m	μ_c	r_{hg}	ϑ_{hg}
Australian dune	90	10	0	50	50	0.80	0.012
Californian outcrop	92.5	7.5	50	25	25	0.25	0.042

During our controlled *in silico* experiments, we computed directional-hemispherical reflectance and transmittance curves using an enhanced implementation of the first-principles light transport model originally known as SPLITS (*Sp*ectral *Li*ght *T*ransport Model for *S*and) [6]. The stochastic formulation employed by this model includes parameters describing the morphology and mineralogy of the particles forming sand-textured soils, as well as the distribution of these particles within the pore space. To enable the reproduction of our *in silico* findings, we have made the enhanced implementation of SPLITS, termed SPLITS-2 [10], available online [11] along with its supporting spectral datasets (e.g., refractive index and extinction coefficient curves).

Each modeled radiometric curve was obtained casting 10^6 rays (per sampled wavelength) onto the samples and considering an angle of incidence of 0° (unless otherwise stated). For the reflectance experiments, we considered the samples' thickness equal to 1 m, a default value that guarantees depth-invariant readings [12]. For the transmittance experiments, we employed a standard thickness value equal to 1 mm [13].

During our *in silico* experiments, we considered four water saturation states: I - dry state ($S = 0$), II - intermediate water-saturated state ($S = 0.5$), III - water-saturated state ($S = 1$), and IV - dry state ($S = 0$) with the grains encapsulated by water films. We assigned to the water film thickness a value of 5 μm, which is consistent with actual experiments involving the presence of water films encapsulating the grains of quartz-sand samples [14].

To quantify the ratios of red to far-red reflected light, we employed the following formula [4]:

$$R/FR_\rho = \rho(645)/\rho(735), \tag{1}$$

where $\rho(\lambda)$ denotes the reflectance at the wavelength λ. The selected wavelengths correspond to the chlorophyll absorption peaks under *in vivo* conditions [4]. For the quantification of the ratios of red to far-red transmitted light, the $\rho(\lambda)$ values were replaced by transmittance ($\tau(\lambda)$) values in Equation 1.

3. RESULTS AND DISCUSSION

To assess the plausibility of our choice of values for the samples' characterization parameters (Table 1) and establish a baseline for our experiments, we initially computed reflectance curves and compared them with their measured counterparts [8]. As it can be observed in Fig. 1, the modeled and measured curves show a close agreement (root mean square errors equal to 0.0068 and 0.0076 for the Australian dune and Californian outcrop samples [10], respectively).

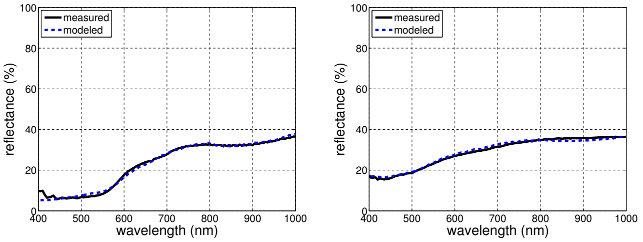

Fig. 1. Comparison of measured and modeled reflectance curves obtained for the Australian dune (left) and Californian outcrop (right) samples.

As shown in Fig 2, the increase in water saturation (from state I to III) resulted in a decrease in reflectance and an increase in transmittance as expected [6, 13], with the differences being more pronounced for the goethite-rich Californian sample. In the case of state IV, even though S is equal to zero, the presence of water films led to slightly smaller reflectance decrease and a larger transmittance than those associated with state II ($S = 0.5$).

Since the reflectance and transmittance variations (from state I to III) were not uniform within the spectral region of interest, the R/FR_ρ and R/FR_τ ratios were also reduced and increased, respectively, as depicted in Table 2. Again, in the case of state IV, the corresponding R/FR_ρ ratios were similar to those obtained for state II ($S = 0.5$), while the R/FR_τ ratios were higher. As also shown in Table 2, the ratios computed for the goethite-rich Californian sample were higher than those computed for the hematite-rich Australian sample, and the R/FR_ρ values were higher than the R/FR_τ values computed for both samples.

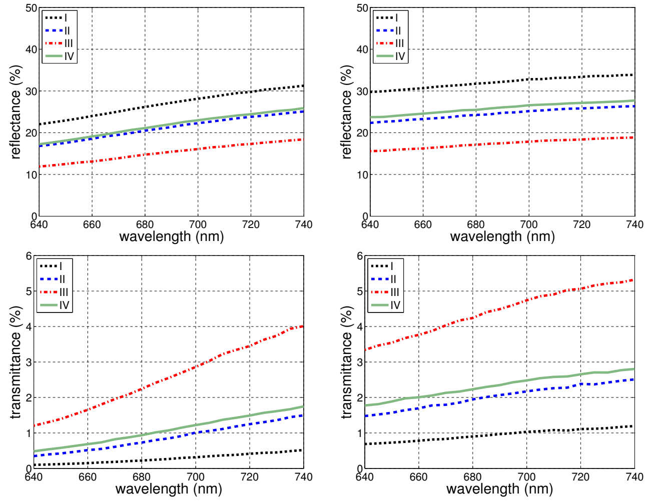

Fig. 2. Reflectance (top row) and transmittance (bottom row) curves (within the spectral region of interest) computed for the Australian dune (left) and Californian outcrop (right) samples considering the four water saturation states (I, II, III and IV) examined in this investigation.

Table 2. Red to far-red ratios calculated for light reflected (ρ) and transmitted (τ) by the selected samples using respectively the reflectance and transmittance values depicted in Fig. 2.

		Water Saturation States			
Ratio	Sample	I	II	III	IV
R/FR_ρ	Australian dune	0.727	0.694	0.671	0.694
	Californian outcrop	0.886	0.861	0.834	0.864
R/FR_τ	Australian dune	0.225	0.271	0.329	0.319
	Californian outcrop	0.604	0.615	0.660	0.654

For completeness, we repeated the experiments considering an angle of incidence of $45°$. As depicted in Table 3, the resulting R/FR_ρ increased while the resulting R/FR_τ ratios decreased. However, the qualitative behaviours matched those verified for an angle of incidence of $0°$ (Table 2).

The effectiveness of vegetation restoration initiatives greatly depends on seed germination. This first, crucial stage stage of a plant's life determines when and where seedling growth begins. Accordingly, to maximize the success rate of seedling establishment, seed germination should be prompted when there is low risk of drought and favourable light conditions for growth [2].

Table 3. Red to far-red ratios calculated for light reflected (ρ) and transmitted (τ) by the selected samples considering an angle of incidence of $45°$.

		Water Saturation States			
Ratio	Sample	I	II	III	IV
R/FR_ρ	Australian dune	0.746	0.7116	0.689	0.714
	Californian outcrop	0.896	0.869	0.845	0.881
R/FR_τ	Australian dune	0.196	0.244	0.303	0.279
	Californian outcrop	0.594	0.583	0.625	0.648

The results of our experiments indicated that the impact of an increase in water saturation (from state I to III) is slightly higher on the R/FR_τ ratios than on the R/FR_ρ ratios. The former are particularly relevant for the germination of photoblastic seeds, whose germination depends not only on the amount, but also on the spectral quality (expressed in terms of the R/FR_τ ratios) of the light reaching them [15]. While the amount affects the stimulation and inhibition of seed germination after long periods of light exposure, the spectral quality affects these natural processes after both long and short periods of light exposure [15].

In most species characterized by photoblastic seeds, the breaking of seed dormancy elicited by light exposure is induced by red light and cancelled by far-red light [15]. Thus, the higher the R/FR_τ ratios, the higher the probability of eliciting seed germination for these species. We note that our experimental results show that these ratios are higher for the goethite-rich sample than for the hematite-rich sample. This suggests that these species' seeds would have a higher chance to germinate in goethite-rich than in hematite-rich sand-textured soils

Conversely, it is worth noting that there are plant species (e.g., *Trachyandra divaricata*, a sand dune inhabiting species found in Australia) whose seed germination is inhibited by red light [16]. Hence, the lower the R/FR_τ ratios, the higher the probability of eliciting seed germination for these species. We remark that the R/FR_τ ratios obtained for the hematite-rich sample during our experiments were lower than those obtained for the goethite-rich sample. This suggests that, from a spectral quality of light exposure point of view, the seeds belonging to these species may have a higher chance to germinate in hematite-rich than in goethite-rich sand-texture soils.

It has been recognized [2, 17, 18] that exposure to low red to far-red ratios may hinder the full development of seedlings and the adult plants' organs. During our *in silico* experiments, the R/FR_ρ ratios calculated for the hematite-rich sample (with respect to all water saturation states) were ≈20% lower than those calculated for the goethite-rich sample. The extent to which the growth of native species in goethite-rich sand-textured soils may be facilitated in comparison with hematite-rich ones may depend, however, on the impact of other abiotic factors such as the availability of nutrients.

Our *in silico* experiments also show that the presence of water films (state IV, with $S = 0$) has an impact on the R/FR_ρ and R/FR_τ ratios similar to that observed for an intermediate state of water saturation (state II, with $S = 0.5$). We note that the state II approximately corresponds to the field capacity of a soil, *i.e.*, the amount of water available for plant uptake until the permanent wilting point is reached [7]. This point, in turn, corresponds to the stage in which the water is held too firmly by the soil grains (forming the encapsulating films around them like in state IV) for plants to extract it [7]. Thus, even though from a light exposure perspective both states result in similar hyperspectral signature and have similar effects on seed germination and plant development, they differ significantly from a point of view of water availability to sustain plant growth.

4. CONCLUDING REMARKS

Arid landscapes are increasingly expanding, seriously compromising surrounding ecosystems [1]. In addition, layers of natural sands are commonly found covering arable fields and crops after being transported from those landscapes by aeolian events. Hence, the spectral quality of light propagated by these ubiquitous materials is not only relevant for the restoration of native vegetation in those regions [2], but also for the control of weeds and the optimization of crop yield [18].

To enhance the technologies employed in the monitoring (*in situ* and remotely) and management of these initiatives, it is necessary to advance the current knowledge about abiotic factors affecting the red to far-red ratios of light propagated by these soils. Our investigation aimed to contribute to this objective. Although further *in situ* experiments must be performed to confirm our *in silico* findings, they strongly suggest that a more comprehensive assessment of these factors and their photobiological ramifications is warranted.

We believe that future research efforts in this area should be directed towards the expansion of such a fundamental knowledge through the coordination of multidisciplinary studies in remote sensing, ecology, agriculture, plant physiology and computational biology, just to name a few fields supporting theoretical and applied investigations in this area. Such synergistic cooperations are bound to play a central role in the achievement of a higher level of environmental protection and ecologically-sustainable agricultural production.

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