Analysis of climate and vegetation variability on erosion using a coupled dynamic vegetation and landform evolution model

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November 23, 2022

Abstract

Variability in precipitation frequency, intensity and duration deeply affect vegetation and erosion yields. Under climate change scenarios, alterations in precipitation are expected but it is not well understood how it could affect erosion rates and what is the role of vegetation on landscape geomorphic response. Traditional erosion models normally include basic representations of vegetation that do not account for the dynamic character of biomass variability and feedbacks with hydrological and erosion/deposition processes. Hence, using a new modelling frameworks that account for the effect of varying vegetation cover on erosion, and that includes climate change scenarios is needed. Here we use a new model: COPLAS, a tool that couples a Landform Evolution Model with dynamic vegetation and carbon pools modules to investigate the response of landscapes to climate change. The vegetation module includes a coupled photosynthesis-stomatal conductance representation that responds to climatic data inputs as temperature, CO2 concentration and water availability. We use the model to simulate the erosional and geomorphic responses of dynamic vegetation in Howard Springs (Australia) to predicted changes in daily precipitation under future CO2 concentrations of about 940 ppm. The model was calibrated using Ozflux site historical data. Catchment scale simulations were run for a period of 100 years for three scenarios (bare soil, constant and dynamic vegetation) using a daily time step. We found that, for our study case, bare soil produces on average 139% more erosion than the constant vegetation case and 124% more than the dynamic vegetation case. Moreover, an increase in precipitation of around 23% induces an increase of 25%, 35% and 43% in the erosion rates for dynamic vegetation, constant vegetation and bare soil respectively, while a decrease in 26% reduces it in 36%, 60% and 59%. This could be explained by the nonlinear relation between erosion and vegetation (higher rainfall induces higher erosion potential which can be counteracted by an increase in vegetation cover leading to a decrease in soil erodibilty). This finding highlights the importance of considering the dynamic character of vegetation in order to understand the nonlinear relations between fluvial erosion and vegetation cover.

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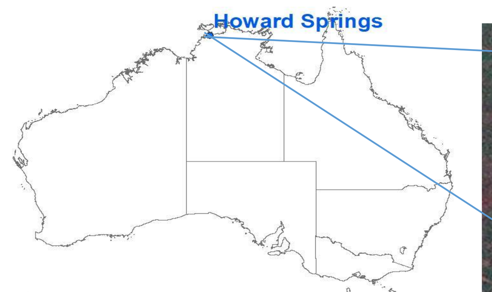
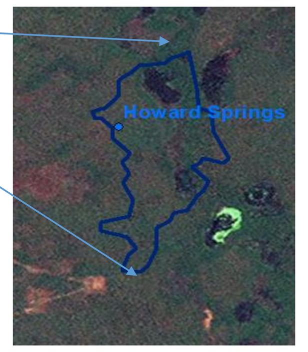
1. Introduction

- Erosion can decrease agriculture productivity, affect infrastructure and ecosystems (e.g. Great Barrier Reef), and generate siltation of watercourses
- Vegetation controls erosion
- Under climate change (CC) conditions alterations in temperature, carbon dioxide concentration (CO_2) and precipitation are expected
- It is not yet well understood how CC could affect vegetation and how could it be reflected on the erosion rates





Study Area: Howard Springs (NT, Australia), 1700 mm/year of rainfall, tropical climate (temperatures between 20 – 33 °C), open woodland savannah governed by Eucalyptus

2. Objectives

- Analyse the response of erosion to CC under variations in temperature (T), carbon dioxide concentration (CO_2) and rainfall (P)
- Develop a model (COPLAS) that couples erosion and deposition processes, with dynamic vegetation and carbon pools modules and that respond to variations with CC

3. Model conceptualization: COPLAS

- COPLAS is a new model which couples erosion, hydrology, dynamic vegetation processes and carbon pools modules (see **Figure 1**)
- The vegetation module includes a coupled photosynthesis-stomatal conductance representation to estimate Net Primary Production (NPP)
- NPP is allocated into five carbon pools: leaves, wood, roots, litter and soil carbon

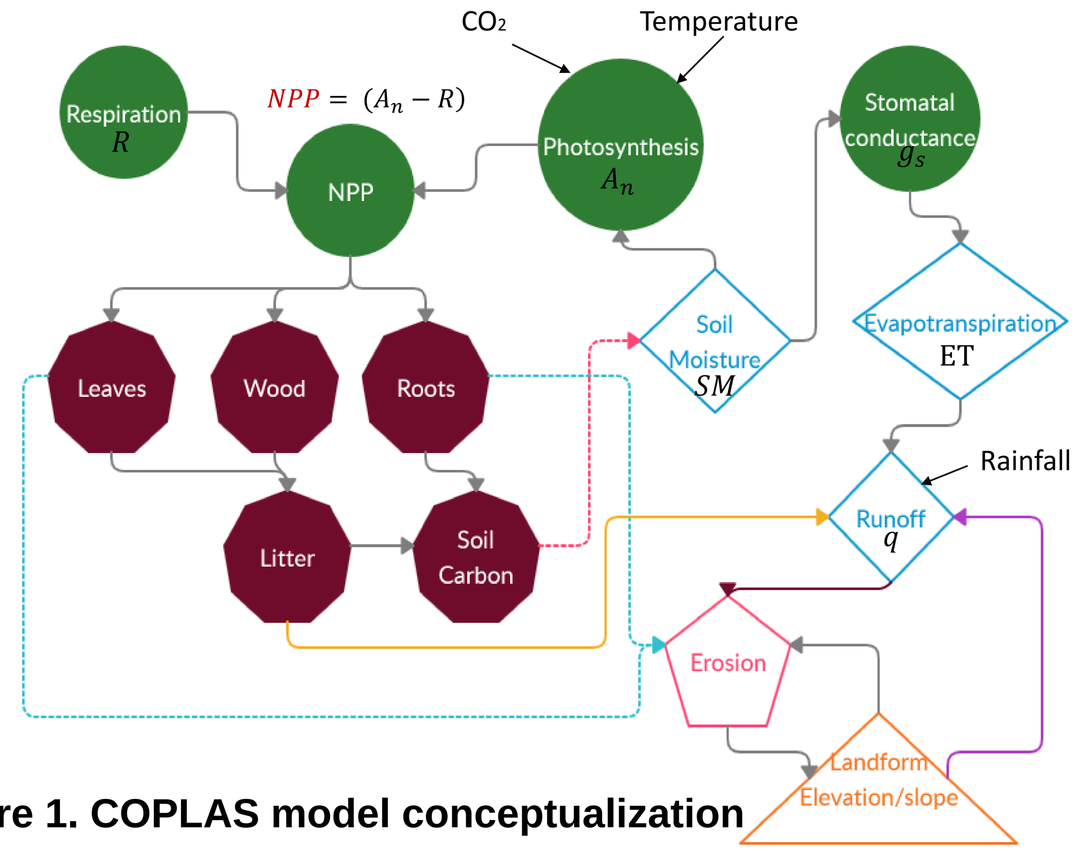


Figure 1. COPLAS model conceptualization

- Variation in elevation depends on the tectonic uplift (U), fluvial (qs) and diffusive erosion (qd), (ƀ) porosity and (ρ) density of the sediment (Willgoose et al., 1991)

$$\frac{\partial Z}{\partial t} = U - \left(\frac{\nabla q_s}{\rho(1-ƀ)} + \nabla q_d\right)$$

- COPLAS uses a hydrology bucket in each cell to estimate soil moisture (SM)

$$\frac{dSM}{dt} = \text{Infiltration}(SM) - \text{ET}(SM) - \text{Percolation}(SM)$$

- Runoff is generated by infiltration (when infiltration capacity is exceeded) and saturation excess (when the soil becomes saturated) and it is routed using a Kinematic Wave approximation (Manning equation for a wide rectangular channel)

$$q = \frac{1}{n} H^{\frac{5}{3}} s^{\frac{1}{2}}$$

3.1 Vegetation Module

- Photosynthesis (An) and Stomatal conductance (gs) are computed in the vegetation module. They respond to changes in T, P and CO_2

$$A_n = \left(1 - \frac{\Gamma^*}{CO_2}\right) * \min[W_c(T, CO_2), W_j(T, CO_2)]$$

CO_2 released by photorespiration — Maximum rate of carboxylation — Electron transport rate

$$g_s = b + f_{sv}(SM)\frac{m(A_n)}{\left(C_s\left(1 + \frac{VPD}{D_{s0}}\right)\right)}$$

Minimum stomatal conductance — Dependency of gs to vapour pressure deficit, carbon assimilation rate and CO_2 — Response of gs to soil water content (indirectly depends on rainfall)

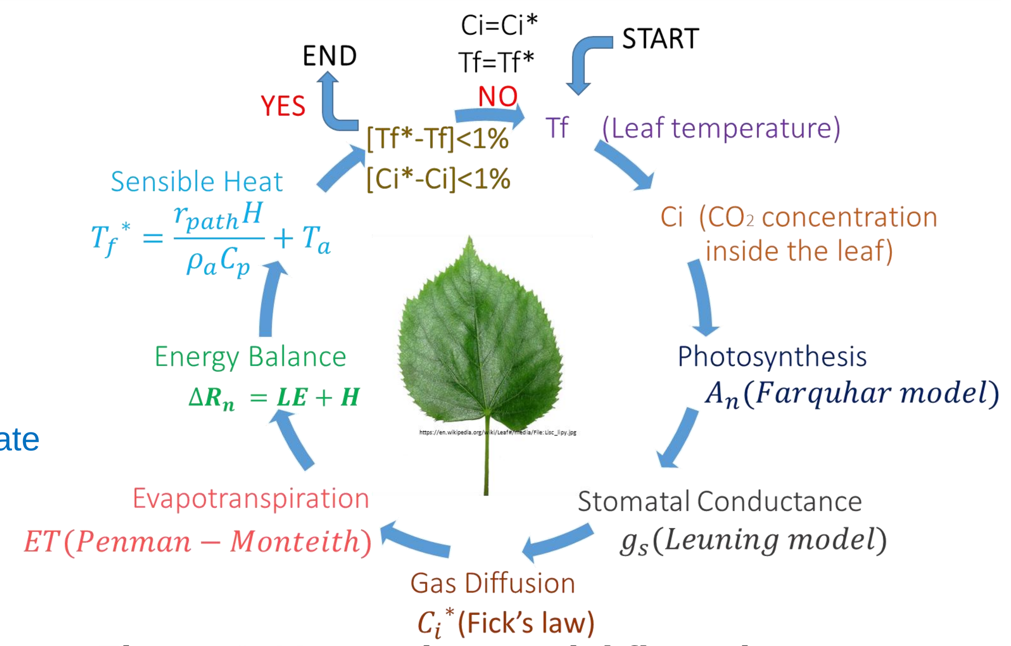


Figure 2. Vegetation model flow chart

- COPLAS uses an iterative method similar to Kowalczyk et al., 2006 to determine the values of the leaf temperature Tf and CO_2 concentration inside the leaf Ci (**Figure 2**)

4. Simulation Scenarios

- Simulations for 100 years, daily time step
- Scenarios under variations in temperature, CO_2 and rainfall (see **Table 1**) were run
- The model was calibrated using data from the OZFLUX Howard Springs station (soil moisture, evapotranspiration and CO2 flux) from 2002 until 2016
- The erosion model was calibrated with caesium-137 measurements found in Loughran & Elliott, 1996.

Table 1. Model scenarios

Variable	Condition	Value	Units	Period
CO_2 concentration	Normal	369	ppm	2002–2016
	Increased	940	ppm	by 2090
Rainfall	Decreased -26%	1331	mm/year	by 2090
	Normal	1802	mm/year	1986–2005
	Increased +23%	2215	mm/year	by 2090
Temperature	Normal	27.0	◦C	2002–2005
	Increased (3.7 C)	30.6	◦C	by 2090

7. Selected References

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5. Results

- Vegetation plays an important role in protecting the soil from erosion: an increase of rainfall generates more erosion; however, the effect is substantially reduced when vegetation is present (Figure 3. A)
- More rainfall triggers more vegetation growth, but this additional protective effect of the new vegetation is not enough to protect the soil from increased amount of rainfall (Figure 3. A)
- An increase in temperature generates more erosion due the reduction in vegetation (Figure 3. B)
- Seasonality is important: less vegetation after the dry season due the higher temperatures and soils less protected when the rainfall events of the wet season occurs bring more erosion (Figure 3. B)
- The combination of temperature and rainfall effects generate 34% and 84% more erosion when comparing with single effects respectively (Figure 3. C)
- Higher temperatures and rainfall generate more erosion while greater CO_2 and lower rainfall reduce it (Figure 3. C)
- CO_2 fertilization effect: increased rate of photosynthesis in plants, and more protection against erosion (Figure 3. D)
- CO_2 effect could controls erosion and overpass the effect of temperature and rainfall (Figure 3. D) (assuming no nutrient limitation)

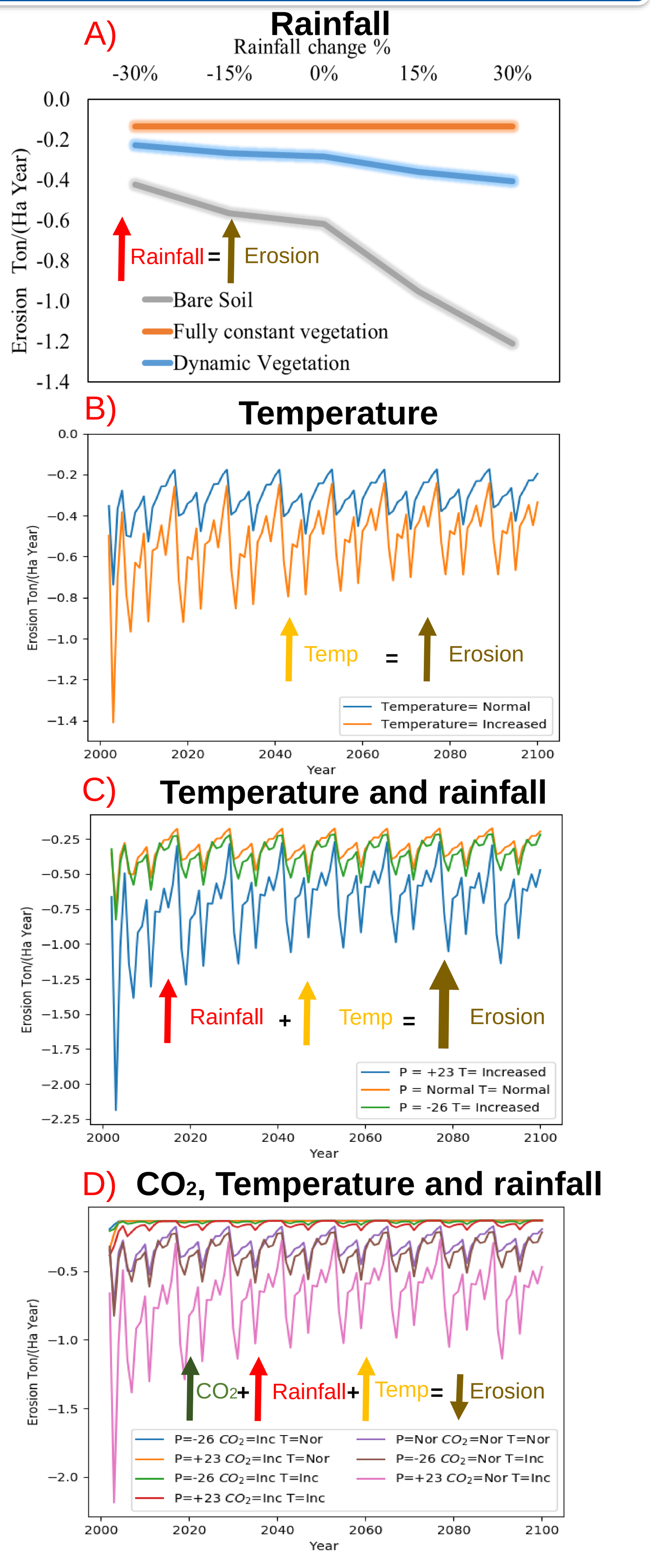

Figure 3. impacts of CC on erosion

6. Conclusions

- Impact of CC on erosion could be different depending on the location, climate scenarios and response of the species
- It was shown the importance of studying the effects together and not separately: different erosion patterns when the effects are combined
- For Howard Springs:
  - Increased temperature and rainfall produce higher erosion
  - Higher CO_2 concentration and less rainfall generates lower erosion
  - If there is no nutrient limitation, CO2 fertilization could control de negative effects of rainfall and temperature on erosion