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Planetary mass, vegetation height and climate

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Research Article

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Abstract

The maximum height trees can grow on Earth is around 122–130 m. The height is constrained by two factors: the availability of water, and where water is not limiting, the pressure available to drive the column of water along the xylem vessels against the pull of gravity (cohesion tension). In turn the height of trees impacts the biodiversity of the environment in a number of ways. On Earth the largest trees are found in maritime temperate environments along the Pacific Northwest coasts of northern California and southern Oregon. These forests provide a large number of secondary habitats for species and serve as moisture pumps that return significant volumes of water to the lower atmosphere. In this work, we apply simple mathematical rules to illustrate how super-terran planets will have significantly smaller trees, with concomitant effects on the habitability of the planet. We also consider the impact of varying tree height on climate models.

Introduction

Approximately, 58% of planets in the habitable zone of stars are super-terrans (http://phl.upr.edu/projects/habitable-exoplanets-catalog). These worlds have greater than an Earth's mass of material and proportionately greater gravitational field strengths (Kite *et al.*, 2009). While the impact of planetary mass on the kind of surface terrain has been considered (Kite *et al.*, 2009; Cowan and Abbot, 2014; Rogers, 2015), the effect on vegetation has not been examined.

If we assume that all super-terrans have sub-aerial surfaces, which may not be true (Alibert, 2014; Rogers, 2015), what will the effect of planetary mass be on vegetation cover? For example, it is understood that the maximum height vegetation reaches on Earth is primarily determined by the availability of carbon dioxide and water (Niklas, 2007; Jasechko *et al.*, 2013) and the height to which water may be transported through the xylem vessels (Jeje *et al.*, 1979; Zimmermann, 1983; Friend, 1993; Zwieniecki *et al.*, 2001*a*, 2001*b*; Koch *et al.*, 2004; Brienen *et al.*, 2017). The latter appears to be principally determined by biophysical constraints imposed by gravity (Niklas, 2007). Water is drawn through specialized vessels, known as xylem. These contain a number of adaptations that facilitate the adhesion of molecules to the wall, as well as the maintenance of a continuous water column between the roots and the atmosphere (Maa, 2017). The evaporation of water through the stomata then draws more water up from below: cohesion tension (Pockman *et al.*, 1995). In this system, there is then a trade-off between the upward pull of cohesion tension; adhesion to the xylem walls; turbulence, generated by fluid flow over the walls of the xylem; and the gravitational pull of the planet (Koch and Fredeen, 2005). This provides a physical constraint on physical transport of water to the leaves, which then impacts biological processes that occur there (Smirnoff, 1993).

In this paper, we apply the physical constraints on water transport to determine the maximum height of vegetation on telluric planets and then apply this information to illustrate how climate is affected in quantitative and qualitative manners. We find that planetary mass grossly constrains the height of vegetation and this, in turn, affects wind velocity and flow structure.

Methods

Mass of super-terran and gravitational field strength

Gravitational field strength varies with mass and radius by equation (1), where g is the field strength at its surface (technically, the distance from the centre of mass), M is the mass of the planet and r is its radius.

$$g = \frac{GM}{r^2}. \tag{1}$$

If the density of the planet is lower than telluric values, then the field strength will scale to lower values at any given depth. However, planets with significantly lower density than the Earth are unlikely to be habitable for complex species, because these worlds will have surfaces capped by deep oceans and/or thick atmospheres (Rogers, 2015). Therefore, for the sake of this gedankenexperiment, we consider planets where the surface is at least partly sub-aerial. While

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this may not be physically reasonable for many super-terran planets, it remains a valuable consideration as many super-terrans orbit red dwarf stars, where substantial loss of volatiles may occur in the first billion years of the planet's existence (Wheatley *et al.*, 2016).

Gravitational field strength and maximum height of vegetation

When the pressure (the water potential) falls below −2 Mpa (an upward suction), evaporation from the air spaces in the leaf tends to drive cavitation or the collapse of xylem vessels. With either the breaking of the continuous water column, or the collapse of the xylem vessel, transpiration will cease and the leaves die (Smirnoff, 1993). This limits tree growth on Earth to heights of 122–130 m on Earth. If we assume that the same physical principle applies then we can extrapolate from the pressure at which cavitation occurs to determine the maximum height of vegetation on a super-terran planet. In principle, there should be a simple scaling between the maximum height of terrestrial vegetation and that on a super-terran. This will be proportional to the gravitational field strength as in equation (2), where h_S is the maximum height of super-terran vegetation, h_E is the maximum height of terrestrial vegetation; g_S is the gravitational field strength on the surface of the super-terran; and g_E is the equivalent on Earth.

$$h_S = h_E.\frac{g_E}{g_S}. \tag{2}$$

Next, one can consider the Hagen–Poiseuille equation (Niklas, 2007), which relates the length of a column of water in a narrow tube to the volumetric flow rate, if the flow is laminar (non-turbulent). This is illustrated in equation (3):

$$J_v = -\left(\frac{\pi r^4}{8\eta}\right)\frac{dP}{dl}, \tag{3}$$

where J_v is the volumetric flow rate, r is the radius of the tube, η is the solution viscosity and the differential function dP/dl is the negative hydrostatic pressure gradient, which relates column pressure, P, with its length, l. While this relationship is based on conditions in idealized laboratory settings, the relationship reliably predicts the maximum height of a tree on Earth to be approximately 100 m.

The cohesion-tension theory gives a hydrostatic gradient (dP/dl) of 0.0098 MPa m^{-1} (Koch *et al.*, 2004; Niklas, 2007). Once the pressure declines below −1 MPa, cavitation of the vessels or loss of turgor in photosynthesising cells limits the viability of the tree (Smirnoff, 1993). Observations by Koch *et al.* show that when transpiration is minimal, the hydrostatic gradient due to gravity is of the order −0.0096 MPa, in line with theoretical considerations; but that this increases to −0.0106 MPa m^{-1} at midday, when transpirational losses and tension are at their greatest (Koch *et al.*, 2004). In Redwoods, the minimum pressure of Koch *et al.* sample was −1.84 + /−0.04 MPa at 108 m height, implying that two-thirds of the impact on xylary pressure was due to gravity.

There is no evidence to suggest that terrestrial vegetation has ever exceeded 122–130 m. While this is marginally more than would be predicted by equation (3), the gain is marginal and the observed maximum height in the fossil record is approximately 130 m (Koch *et al.*, 2004; Koch and Fredeen, 2005). Irregularities in true xylem vessels should reduce flow rates, while increases in the diameter facilitate faster transpirational flow, but increase the likelihood of cavitation.

As the theoretical and observational decline in xylary pressure agree closely, we can use the value 0.01 MPa m^{-1} as a constant in further calculation. This approximates the upper end of the narrow range of pressures that exist in xylem throughout the terrestrial day. As the pressure varies with the acceleration due to gravity, g, we can derive the simple relationship between the acceleration due to gravity, g, on Earth and a super-terran in relationship to this factor. Applying the constant 0.01 MPa m^{-1} gives us equation (4).

$$-1.0 \le h\frac{g_E}{g_S}0.01, \tag{4}$$

where h is the maximum tree height; g_E and g_S have the same meaning as in equation (2); and 0.01 is an approximate constant that is derived from cohesion-tension theory and observation (Koch *et al.*, 2004; Koch and Fredeen, 2005). Rearranging equation (4) gives us equation (5) which allows us to determine the maximum height as:

$$h \le 100\frac{g_E}{g_S}. \tag{5}$$

Therefore, in the absence of compensatory mechanisms, the maximum tree height on a super-terran is always <100 m. Empirically, we can adjust the output of this equation to match terrestrial observation 122–130 m versus the theoretical value of 100 m, by the addition of a further dimensionless constant 1.2, which covers the additional effects of other adaptations. The value '100' becomes '122–130'. However, physiologically, there is a limit to how much this figure can be increased, through widening of the xylem vessels or changes to the composition of the xylary fluid (Jei and Zimmerman, 1979; van Ieperen *et al.*, 2000; Niklas, 2007).

Finally, to determine maximum tree height, based on planetary mass and radius, we substitute equation (1) into (5) to get equation (6). This is then in a usable form using astrophysically available data.

$$h \le 100\frac{M_E r_S^2}{M_S r_E^2}, \tag{6}$$

which may be written as:

$$h \le 100 M_E r_S^2 M_S^{-1} r_E^{-2}, \tag{7}$$

where M_E and r_E are the mass and radius of the Earth, respectively. M_S and r_S are the corresponding mass and radius for a super-terran (or any exoplanet). If these values are known, then they can be used directly to determine the maximum height of vegetation, where water movement is driven by cohesion tension.

Relevance – Earth mass and radii

For reasonable planetary masses and Kepler observations, this likely limits masses to <7-Earths (Dressing and Charbonneau, 2015; Zeng *et al.*, 2016). With terrestrial compositions, this limits their radii to <1.6-Earths (Rogers, 2015). This may well be an upper limit as Kepler data suggests that at around 1.6-Earth radii, there is an abrupt decrease in planetary density, suggesting that these planets rapidly deviate from telluric structures, towards Neptune-like organizations (Rogers, 2015). Planets in the range 1.4–1.6-Earth radii may be aquaplanets. Therefore, realistically in terms of radii, only those planets with radii <1.4-Earths may be worth considering.

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Determination of g using a mass–radius relationship

In order to constrain g for a variety of viable planetary systems, where only r or M is known with precision, we can use equation (2) from Zeng *et al.* (2016). This has a reasonably good fit for a variety of planets, including the Earth and Venus. This is described in equation (8) as:

$$\frac{R}{R_E} = (1.07 - 0.21.\text{CMF}).\left(\frac{M}{M_E}\right)^{1/3.7}, \quad (8)$$

where R is the radius of the exoplanet, R_E is the radius of the Earth; M is the exoplanet mass; M_E the mass of the Earth and CMF is a function, relating to the mass of the core in relation to the mass of the planet as a whole, where the value 0.30 appears to fit most observed planets in the range 0.8–7-Earth masses (Zeng *et al.*, 2016).

Frictional coefficients and wind velocities on low relief and vegetation planets

Terrestrial surface winds have steadily reduced over the last four decades. Measurements from 1979 until 2008 show a reduction in mean wind velocities (stilling) on the order of 5–15% (Vautard *et al.*, 2010). A significant proportion of this effect appears attributable to increases in vegetation height. Mathematical modelling suggests reductions in wind velocity at the surface can be attributed using the following relationship from Vautard *et al.* (2010).

$$\delta U = a\ln\left(\frac{z_0}{z_{0c}}\right), \quad (9)$$

where δU is the change in velocity of surface winds to a height of 10 m; a is a constant, which has a value of 0.48–0.37 m s^{-1} when the surface is roughened (the lower end pertaining to a generic increase in roughness; and the upper value pertaining to an increase in the roughness of grassland); z_{0c} is a standard roughness value and z_0 representing the new value caused in this instance by an increase in vegetative cover. An increase in roughness height by a factor of two (a doubling in vegetation height) would reduce wind velocities by 0.26–0.33 m s^{-1} (Vautard *et al.*, 2010). This amounts to a reduction in mean, surface winds of 5–15% over continental areas. These impacts on wind velocity are now applied to two aspects of super-terran habitability. For simplicity, we adopt the approximate mean value of 0.30 m s^{-1} for a doubling in height of vegetation.

Results

Vegetation height

The maximum height to which vegetation can grow on any planet is given by equation (6). Application to possible exoplanets is illustrated in Table 1. Reasonable planetary masses are included, with the higher masses likely only applicable with increasingly significant losses of planetary volatiles through atmospheric stripping (Wheatley *et al.*, 2016). Otherwise, one presumes the surface, if habitable, would be drowned in oceans (Cowan and Abbot, 2014).

In general, if one assumes that vegetation on an exoplanet has the same basic necessities as terrestrial plants, then one would expect greater abundances and heights of vegetation as one moves towards areas of greatest precipitation (Pockman and Sperry, 2000; Niklas, 2007; Brienen *et al.*, 2017; Rosell *et al.*, 2017; Liu and El-Kassaby, 2018). On asynchronously, rotating planets, like the Earth, the distribution of precipitation is dictated by the mass, spin and energy supply to the surface and atmosphere. We, therefore, assume that the distribution of vegetation height will follow the same rules as on Earth.

Impact of reduced vegetation height on surface wind velocities and climate models

Equation (7) shows that an increase in plant height by 10 m reduces surface wind velocity by around 0.3 m s^{-1}(Vautard *et al.*, 2010). Winds become more turbulent as they flow over trees (Frederick, 1961; Marshall, 1998; Mohamed *et al.*, 2015). Therefore, we can deduce that the greatest impact of trees on wind velocities will be on planets with the lowest masses, with all other variables kept constant. At greater masses, vegetation height is lower. Indeed, on a 3-Earth-mass planet, the wind velocities are likely to be approximately 3 m s^{-1} faster in forested areas than would be found in a similar climatic region on an Earth-mass world. This obviously depends on the precise means of water transport, but if cohesion tension is the driving force, this is a reasonable expectation.

Effect on climate models for synchronously rotating worlds

In principle, if the planet is telluric and with land, these values should apply generically to planets of different masses, irrespective of the underlying nature of the planet concerned. However, the distribution of precipitation is important in restricting the maximum height. Increased water stress reduces carbon dioxide fixation and with it the propensity for the tree (or other vegetation) to grow to its full potential (Smirnoff, 1993). In general, one would expect a greater tensile force in areas where water stress is greatest. In hot, dry areas, the evapotranspiration rate will be higher (Kitaya *et al.*, 2000; Jacobsen *et al.*, 2010; Maa, 2017; Liu and El-Kassaby, 2018) but the supply of water through the xylem will be lower. If nothing else is altered then there will be a greater propensity for the water column to break, leading to a loss of cohesive-tensile force along the column length (Pockman and Sperry, 2000; Woodruff *et al.*, 2004; Olson and Rosell, 2013).

On tidally locked planets, the focus of precipitation is at the sub-stellar point (SSP, Haqq-Misra, *et al.*, 2017). In that sense, terrestrial vegetation broadly increases with height in response to both temperature and humidity. Therefore, in locations distal to the SSP, one would expect at best very limited distributions of low height vegetation. The exception would be in areas where orographic rainfall was significant (Stevenson, 2019, in press). However, these may be very limited in distribution, particularly on planets of higher mass, where vertical relief is likely to be more limited (Kite *et al.*, 2009; Cowan-and Abbot, 2014).

While it is beyond the scope of this article to consider climate impact in terms of precipitation, one would consider two *likely* effects. In the first, the overall reduction in wind velocity caused by surface vegetation might broaden the focus uplift and enhance precipitation over a larger area than would be seen when surface frictional forces are smaller. This means that there will be a greater impact on planets with lower masses, as the frictional effects of vegetation will be less. Secondly, terrestrial vegetation is responsible for the greatest transport of water from the soil to the atmosphere over continental areas (Jasechko *et al.*, 2013). Jasechko *et al* show that 80–90% of the return of precipitated water from the soil

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Table 1. Variation in tree height with *g*

Planetary mass (Earths)	Planetary radius (Earths)	Surface gravity (g ms^{-2})	Theoretical maximum height (m)	'Fudge factor' (×1.22) maximum tree height (m)
1.0	1.00	9.81	100.00	122.0
1.5	1.15	11.13	88.14	107.5
2.0	1.20	13.62	72.03	87.9
2.5	1.30	14.51	67.61	82.5
3.0	1.35	16.15	59.10	72.1

The value of '*g*' for various planetary masses and radii is derived from Zeng *et al.*, 2016. The fudge factor is simply an empirical add-on, based on terrestrial observations as described in the text.

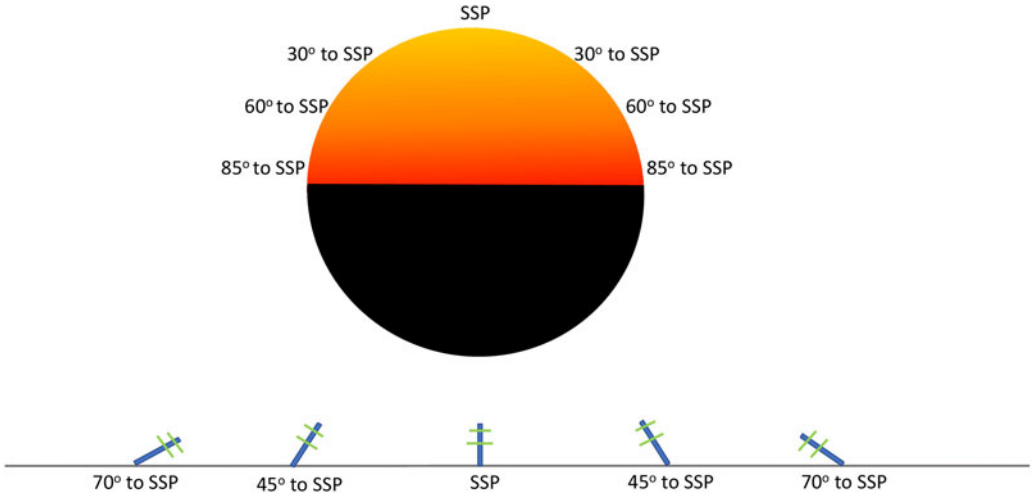


Fig. 1. The angular separation from the sub-stellar point and the effect on the angle of plant growth. If plants orientate themselves rather than their leaves, then plants will have to adopt strategies to prevent rupture of the trunk or limbs.

to the atmosphere is through transpiration. Higher wind velocities cause increases in evapotranspiration rate (Kitaya *et al.*, 2000). Therefore, in areas of lower vegetation, evapotranspiration will be greatest, because wind velocities will be greatest: this will be experienced on the surfaces of planets of higher mass. This will lead to higher precipitation rates towards the SSP in higher mass planets, because there will be more water in the atmosphere above forested areas of lower height.

Moreover, in general, most climate models for synchronously rotating planets have >90% of the precipitation falling within 30° either side of the SSP (Boutle *et al.*, 2017). Some are more restrictive than this (Merlis and Schneider, 2010). While these models apply specifically to aquaplanets, the climate models do offer a means of interrogating climate on telluric planets with land areas (Stevenson, 2018). If we consider realistic distributions of precipitation and consider the physiological impacts of this on water transport (Friend, 1993; Pockman and Sperry, 2000; Brienen *et al.*, 2017), one should expect vegetation with lower heights in areas removed from the SSP on synchronous rotators. Thus, frictional effects will vary from distance from the SSP, being greatest closest to it.

Discussion

In this paper, we show that changes in planetary mass result in changes in vegetation height, which then impacts climate models.

One immediately may ask, is it reasonable to quantify photosynthetic organism growth on a planet if we haven't yet observed it? After all, if we set terrestrial benchmarks, are these applicable to extraterrestrial organisms? In short: yes. One may well fancifully produce some sort of producer with an organ that can pump fluids from its roots to its branches. However, for a photosynthetic organism to do so, it must harvest and store significantly more energy during the day than is observed in all terrestrial producers. Operating the equivalent of a muscular system requires a significant energy input of the kind not seen in any producer on Earth. Therefore, one returns to the cohesion-tension system as the most likely system through which fluids are delivered from the soil to the atmosphere in a producer (Vogel, 1981; Friend, 1993; Pockman *et al.*, 1995; Thompson and Holbrook, 2003; Woodruff *et al.*, 2004; Koch and Fredeen, 2005; Niklas, 2007; Kim *et al.*, 2014; Maa, 2017; Rosell *et al.*, 2017). Therefore, the model applied here works and shows a simple but testable model, whereby the greater the planetary mass, the lower the height of the vegetation.

In principle, the effect is then to reduce frictional coefficients for vegetation for planets of higher mass. This matches the overall reduction in friction that will be associated with surfaces of lower topographical relief on planets of greater mass (Cowan and Abbot, 2014). Therefore, it is essential that once climate models for planets with continental surfaces are considered, the effect of vegetation height and topographic relief are incorporated.

A final thought concerns the manner in which vegetation might grow in response to habitation of synchronous rotators. While, not formally considered here, one notes that terrestrial vegetation grows towards the light. As the Sun moves across the terrestrial sky, vegetation primarily grows in a vertical direction.

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However, on a synchronous rotator, light constantly illuminates the surface from one direction. Consequently, plants must either grow their stems towards the light, or orientate their leaves towards it, while the stems grow vertically. This effect varies with the angular separation from the SSP (Fig. 1). If the former strategy is adopted, plants will be compelled to grow at increasingly shallow angles with respect to the planetary surface as one approaches the terminator. In this regard, vegetation will lower in height as one moves away from the SSP and towards the terminator, irrespective of any effect imposed by precipitation. This will also reduce the frictional coefficients in a manner dependent on angular separation and (by inference) the angle of illumination. If this strategy was adopted, the effect of limb and trunk weight would need to be included.

Branches and trunks in terrestrial vegetation breaks at specific wind velocities, which applies a force over which the trunk is no longer able to accommodate the increased strain through bending. This tends to happen at 42 m s^{-1} (Xi *et al.*, 2008; Virot *et al.*, 2016). However, while such wind velocities are unlikely to be a factor on synchronous rotators (Kopparapu *et al.*, 2016), the equivalent force would be produced by growth at an angle. Plants, may adopt various strategies to maximise the capture of incident radiation. This could include dropping new rooting stems from the diagonally extending trunk, or simply by growing low, over the ground or over one another. Fortunately, as the majority of habitable planets that orbit red dwarfs are likely to be slowly rotating, airflow will be radially directed towards the SSP and, therefore, in the same direction as vegetation is orientated.

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