

ARTICLE

Experimental Evidence of Plant Thermoregulation and Its Implications for Climate Stability

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ABSTRACT

Ongoing experiments reveal that plants of different species actively regulate their surface temperature by means of varying their rate of evapotranspiration. The overall cooling under hot weather conditions and bright sunlight may amount to as much as 20 °C. That degree of cooling is vital in order to counteract the relatively low albedo of the leaves and to leave the plant surface cooler than the ambient temperature. In colder, cloudy conditions, plants reduce their evapotranspiration, with resulting surface temperatures that may exceed ambient temperatures. The evolution of angiosperm forests, on account of their vascularised leaves and relatively high rate of transpiration, may have been a major factor in the cooling of the planet from 100 million years ago, when average global surface temperatures were 6 °C higher than today. In addition, a high rate of evapotranspiration will have triggered the inflow of humid air from the ocean, thereby enabling the flourishing of the forests across continents. Physical experiments carried out by the author indicate that water vapour condensation results in partial pressure changes, with resulting airflow, consequently, as physics dictates, cloud condensation over forests will give rise inevitably to ocean-to-continent airflow. Given the role of the forest-derived biotic pump in generating flying rivers over the Amazon Basin, deforestation can result in hydrological collapse. The regeneration and recovery of forests can help cool the Earth's surface by at least 1 °C globally.

Keywords: Thermoregulation; Biotic Pump; Hydrological Cycle; Global-Warming; Angiosperm Evapotranspiration; Global-Cooling

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1. Introduction

To survive, plants need water. In higher plants, water is drawn up through the roots and, under pressure, moves up the stem in narrow xylem channels to the leaves and from there, is transpired, as vapour, through minute stomatal pores into the atmosphere. Water adds mechanical strength to the tissues, preventing wilting and, in combination with CO₂, uses photosynthetic energy from the sun to convert to carbohydrates. All that is well-known. What is less well-known is the power of plants to cool their surroundings, not just by providing shade as in a woodland but, by means of transpiration, which absorbs significant amounts of solar energy as the stream of water is vaporised, to bring about a measure of cooling^[1-7].

Because of global warming, we are now experiencing more frequent climate extremes, like prolonged heat waves, droughts, and flash storms. How do plants respond to warmer temperatures? Do they warm up accordingly, or can they adjust the flow of water through the stomata to counter the warmer temperatures imposed on them by global warming?

To test whether plants can regulate their surface temperature, experiments were carried out on a number of different species under different environmental conditions, as determined by what the weather was doing on that particular day. The results revealed that plants actively adjust the transpiration rate to regulate the surface temperature of their leaves. Under bright sunlight and mid-summer temperatures as experienced in a South-facing Conservatory in Southwest UK, the plants increased the transpiration rate as the external temperature rose. Meanwhile, under cooler conditions, for instance, as clouds passed overhead, the transpiration rate would fall accordingly. In effect, a highly significant correlation was found between the per-second change in external temperature and the release of water vapour from the leaf surface, as measured by calculations of the changes in the absolute humidity in g of water vapour per cubic metre of air (see Section 3 and Equations 1–11)^[5-7].

In order to obtain absolute humidities of the samples and from that data the degree of surface cooling, sensors were employed to measure temperature, relative humidity, and barometric pressure. The corresponding application of physics provided the results, as shown in the following figures, including those indicating highly significant correlations (Equations 1–11).

2. Methodology and Ideal Gas Physics

The use of Rotronics hygrometers, HC2A, hardware version 3, placed directly over the surface of leaves, with a 2 mm gap between the leaf and hygrometer, of different plants and over artificial turf, enabled the simultaneous measurement of relative humidity and temperature for different leaves and substrates, including a basin of water. The barometric pressure, relative humidity and temperature were obtained from a CONTROLdisc-max-i-004, the latter being used for measuring ambient conditions.

Standard physics were applied throughout to interpret the experimental results. The three variables of temperature, barometric pressure and relative humidity were used to calculate the partial pressure of water vapour (ppwv) using the exponential equation of Clausius-Clapeyron. Since, at an atmospheric pressure of 1013.25 hPa, p_2 , water boils at 373 K, represented as T_2 , it is possible to substitute for p_2 and T_2 . The saturated partial pressure of water, p_1 , at each temperature, T_1 can be determined as follows^[5,6]:

$$\ln \frac{p_2}{p_1} = \frac{Q(T_2 - T_1)}{RT_2 T_1} \quad (1)$$

The above equation can be rewritten as:

$$\log p_2 - \frac{Q(T_2 - T_1)}{RT_2 T_1 2.303} = \log p_1 \quad (2)$$

where Q , the latent heat of evaporation, is 40.65 kJ mol⁻¹, R , the ideal gas constant, is 8.31 J K⁻¹ mol⁻¹. The actual partial pressure of water vapour, p_1 , is given by multiplying the result by the relative humidity, RH, as measured by the hygrometers. The air density is obtained through the use of the equation of state for ideal gases^[8,9]:

$$p = \rho RT \quad (3)$$

Where p is the barometric pressure in hectopascals (hPa), ρ is the air density in kgm⁻³, R is the ideal gas constant, J K⁻¹ mol⁻¹, and T is the temperature in Kelvin. To obtain q , the absolute humidity of water vapour in kg per kg of moist air, the formula is used where 0.621 (18/29) is the ratio of the effective molecular weights of water vapour and dry air:

$$q = \frac{0.621 p_{wv}}{p_{atmos}} \quad (4)$$

Where p_{atmos} is the barometric reading and p_{wv} is the partial pressure of water vapour, as calculated, at the same time of

reading. When the value of q is applied, it gives the value of R , the ideal gas constant for moist air, as water vapour is added or removed. To calculate the specific humidity, h (water vapour in g/m^3 of moist air), the values of q and ρ (the air density in kgm^{-3}) are required, as are the values for R . Since R varies with the degree of humidity, the values $287 \text{ J K}^{-1} \text{ kg}^{-1}$ for dry air and $461 \text{ J K}^{-1} \text{ kg}^{-1}$ for water vapour are used in the equation:

$$R = 461q + (1-q) 287 \quad (5)$$

The air density, ρ , in kgm^{-3} , is obtained using the ideal gas equation, where the barometric pressure is given in pascals (Pa):

$$Pa = \frac{R T}{\rho} \quad (6)$$

The humidity, h , of moist air, in g/m^3 will be obtained from the proportion of humidity, q , in a given air density ρ :

$$h = q\rho 1000 \quad (7)$$

Mass, M , multiplied by acceleration provides the kinetic energy values (Ws) for changes in the partial pressure of water vapour, $\Delta Pa/\Delta t$, and that of change in air density per second, $\Delta\rho/\Delta t$. The gravitational constant, g , is taken as 9.81 ms^{-2} , and t is the time in seconds:

$$J \text{ or } Ws = 9.81 \frac{\Delta\rho}{\Delta t} \text{ and } J = \frac{\Delta Pa}{\Delta t} \quad (8)$$

Thermodynamically, it is relatively straightforward to calculate the temperature increase in each kilogram of air as condensation takes place:

$$\Delta T = \frac{LM}{C_p} \quad (9)$$

Where T is Kelvin; L is the latent heat of vaporisation of water vapour, $2.2583 \text{ MJ kg}^{-1}$, M the mass in kg and C_p is the heat capacity of dry air at constant pressure, $1000 \text{ J kg}^{-1} \text{ K}^{-1}$. McIlveen^[6] gives the example of 1 g of water vapour condensing into liquid water and shows that it will warm 1 kg of air by 2.5°C . The condensation of water vapour leaves the remaining air denser, which combined with its expansion into the partial vacuum from condensation causes the temperature to decline. The relationship between temperature change and absolute humidity is:

$$\Delta T_v = 0.621 \Delta q T \quad (10)$$

Where T_v is the virtual temperature of the water vapour as it condenses; T is the actual temperature of the air, and q is the specific humidity, $\text{kg water vapour per kg moist air}$. For the condensation of one gram of water vapour in 1 kg of air at 0°C , the temperature reduction would be 0.17°C . Again, multiplying the small temperature reduction, ΔT_v , by C_p , the heat capacity of dry air at constant pressure, $1000 \text{ J kg}^{-1} \text{ K}^{-1}$, the negative kinetic energy can be calculated. That calculation is equivalent to the net negative kinetic energy derived from the change in the water vapour partial pressure. Hence^[5]:

$$J \text{ or } Ws = \frac{\Delta Pa}{\Delta t} m^3 = 1000 \Delta T_v m^3 \quad (11)$$

To obtain the absolute humidity of the samples and the energies involved in transpiration a number of steps have to be followed, utilising the above standard equations.

Three separate HCA2 hygrometers can be linked, via USB, to the Rotronics software, thereby permitting simultaneous measurement of relative humidity and temperature of all three hygrometers. The use of two computers therefore enables the comparative measurements of humidity and temperature at the same time for up to 6 hygrometers. In the experiments on thermoregulation, 4 hygrometers were used.

3. Results

By subtracting the absolute humidity of the ambient air from the absolute humidity at the leaf surface, the former measured several metres away from the vegetation, it is possible to calculate both the transpiration rate and the degree of cooling in Kelvin/Celsius. From ideal gas physics, Equations 1–11^[5,6], the heat capacity of air amounts to $1000 \text{ J kg}^{-1} \text{ K}^{-1}$. Each gram of liquid water requires 2258 J to transform into vapour.

The experiment of 11th April was carried out in the open, under bright sunlight, the insolation measured per minute, with a Seaward Solar Survey 200 R, indicating an average 945 W/m^2 . In addition to the ambient air control, three specimens were used: grass turf, artificial grass and a bowl of water. **Figure 1** shows the significant difference between the absolute humidity (q , g/kg^{-1} air, Equation 4) of the ambient air versus that of the grass turf. The absolute humidity of the water specimen is marginally higher than the ambient air. Under the sunny conditions of that day, with ambient temperatures of around 22°C , transpiration from the grass

significantly exceeds evaporation from the surface of the water. The artificial grass has the lowest absolute humidity at 7.5 g/m^3 compared to peak values of 16 g/m^3 for the grass.

Figure 2 shows the latent heat difference in kW between that of the control and those of the other samples, the grass, artificial grass and water. By using Equation 9, the kilowatt differences, derived from the absolute humidities between the air control and the samples, can be directly viewed

in terms of degrees Celsius (Kelvin). The high fluctuations seen in the total cooling achieved by the grass indicate a close response to changes in the ambient temperature.

Those high fluctuations are indicative of a high correlation which exists between the rates of transpiration in absolute humidity terms of the different vegetation samples and the changes in temperature, with the latter showing a cooling in response to a higher rate of transpiration.

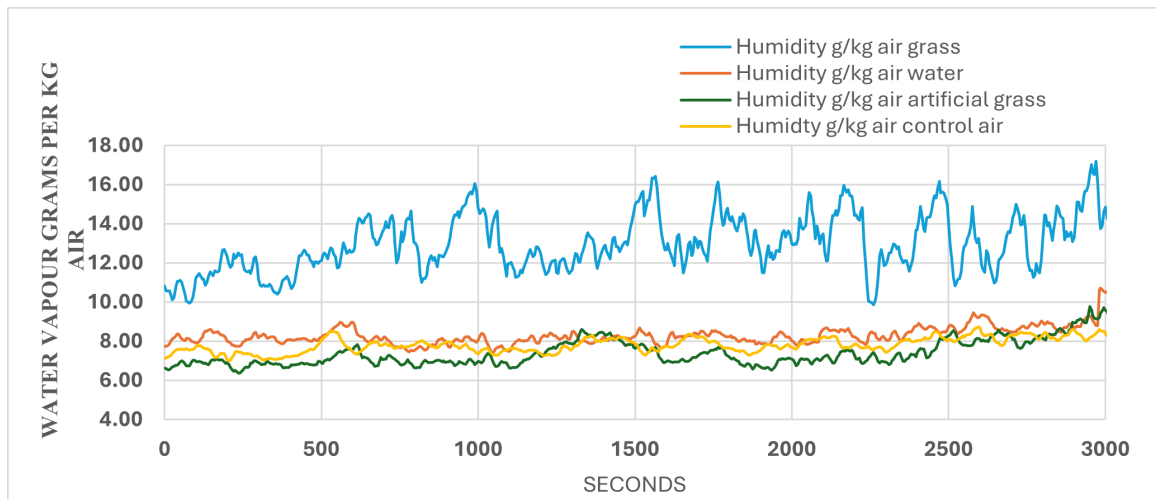


Figure 1. Absolute humidity grams per cubic metre (g/m^3).

Note: Experiment on 11th April, 2025. The absolute humidities (q) in g/m^3 for grass turf, artificial grass, ambient air, and water.
Source: @Peter Bunyard.

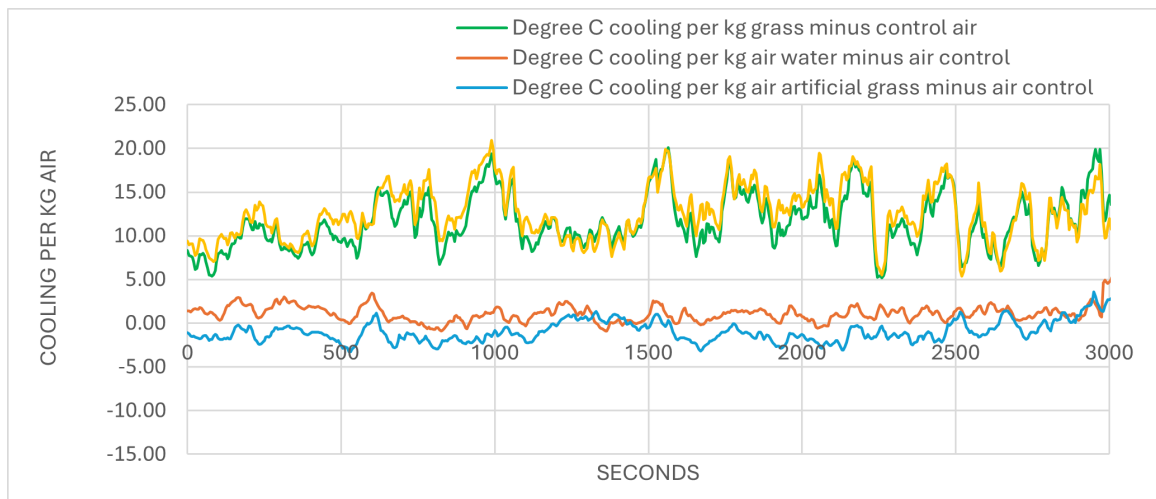


Figure 2. $^{\circ}\text{C}$ cooling per kg air per sec.

Note: Experiment 11th April, 2025. The heat capacity (Equation 9) converts latent heat kW directly into $^{\circ}\text{C}$ ($1000 \text{ J kg}^{-1} \text{ K}^{-1}$).
Source: @Peter Bunyard.

From experiments in which the surface cooling of temperate plants, including a sward of grass species and cyclamen, is compared with that from the tropical graviola (*Annona muricata*), the temperate vegetation appears to pre-

fer for a surface temperature close to 30°C rather than the 35°C of the graviola. To obtain that degree of cooling, the temperate plants demonstrate a higher transpiration rate compared with the graviola. In the experiment of 30th May (**Figure 3**),

we see that the graviola surface temperature remains several degrees Celsius above the cyclamen and grass sward. Meanwhile, at its peak, the temperature of the false turf is 43.5 °C.

Figure 4 shows the absolute humidities of the samples.

The cyclamen has the highest humidity, averaged at about 25 g of water vapour per cubic metre of the air, the grass shows 23g/m³, and the graviola 21 g/m³. Both the artificial turf and the ambient air have an absolute humidity that averages at 14 g/m³.

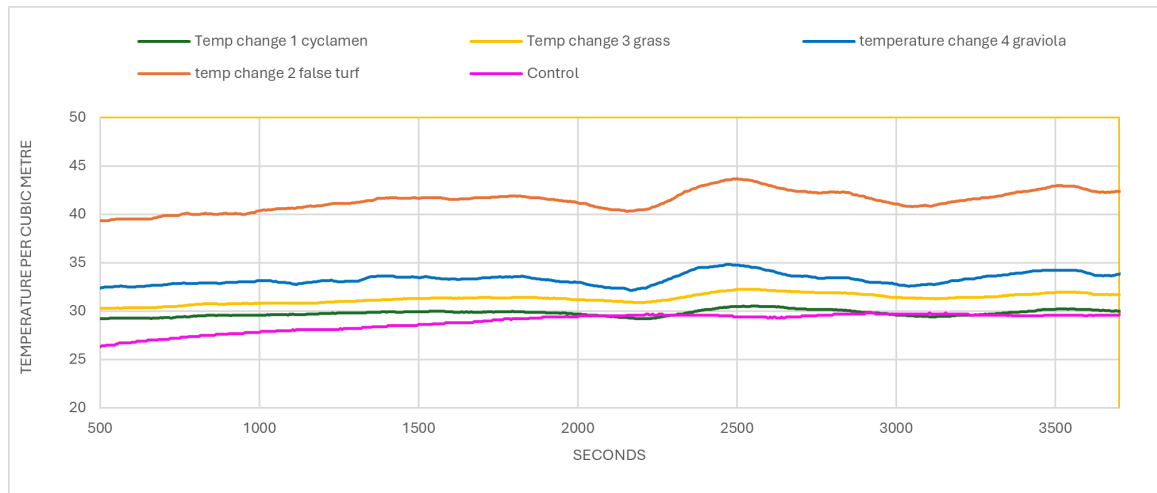


Figure 3. Surface temperature 30/05/2025.

Note: Experiment 30th May, 2025. Leaf surface temperatures.
Source: @Peter Bunyard.

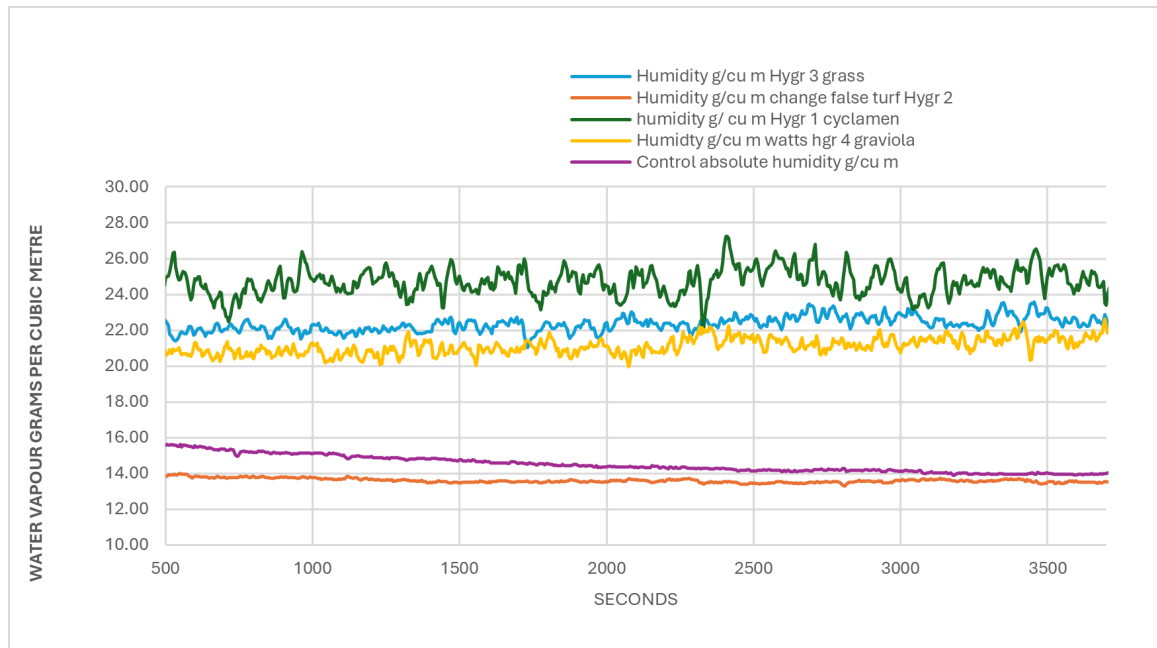


Figure 4. Absolute Humidity grams per cubic metre (g/m³).

Note: Experiment 30th May. Absolute humidities. Note that the absolute humidities of the false turf and the control are, as expected, of a similar order.
Source: @Peter Bunyard.

In the experiment of June 19th, 2025, (Figures 5 and 6), the insolation in the conservatory measured 440 W of energy and the transpiration rate, measured at the surface of a leaf of a tropical tree, Graviola (*Annona muricata*), amounted to

6 g of vapour per second per kg of air. The conversion into latent heat energy amounted to 16 kW per second per cubic metre, or 13 kW per second per kilogram of air. Taking the heat capacity of air into account, the graviola leaf therefore

cooled its surface by 13 °C. **Figure 6** shows the high correlation between the absolute humidity change of the graviola leaf and the change in temperature at the leaf surface.

Under sunny conditions, cooling is vital for vegetation with green leaves. In the experiments, the temperature of false turf, with a similar green colour and therefore similar albedo, was measured. The control temperature in the

conservatory during the experiment was 27 °C compared to 46.8 °C for the false turf, a difference of 19 °C. The graviola leaf, meanwhile, displayed a surface temperature of 34.3 °C (**Figure 5**). That finding complies with the calculated 13 °C cooling from the rate of transpiration. With no transpiration, the graviola leaf would have a similar raised temperature as the false turf.

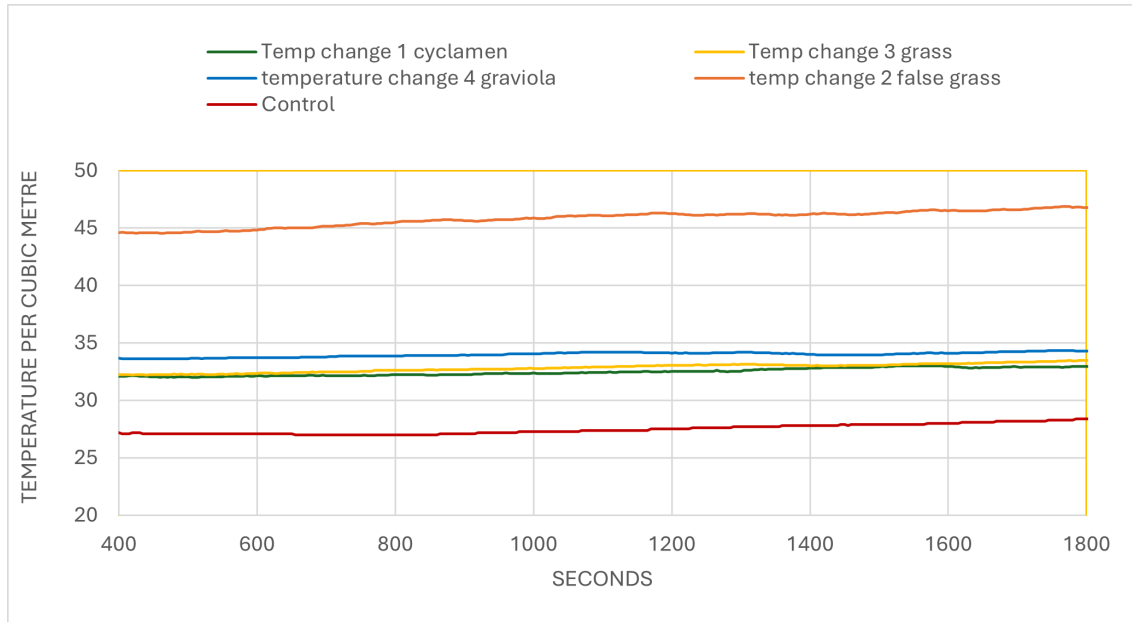


Figure 5. Temperature per cubic metre per sec.

Note: Experiment 19th June, 2025. Surface temperatures of the different media. The calculated cooling, 13 °C of the graviola accords with the measured temperature difference of 12.5 °C between the artificial grass and the graviola.

Source: @Peter Bunyard.

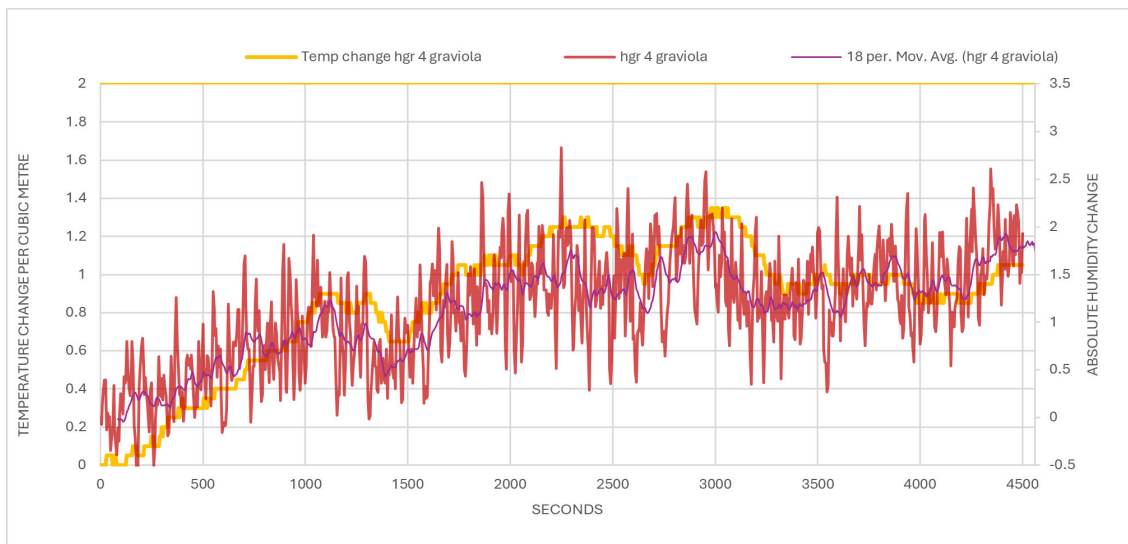


Figure 6. Temperature change degree C per sec versus plant absolute humidity change.

Note: Experiment of 19th June, 2025. Graph showing the tight correlation between the change in temperature and the change in absolute humidity of the tropical tree, graviola. Increases in temperature lead immediately to an increase in absolute humidity. The multiple oscillations of the graviola leaf humidity indicate a physiological reaction to temperature change.

Source: @Peter Bunyard.

The high correlation between the per second change in absolute humidity and the leaf surface temperature is revealed in the experiment of 31st July, 2025, (Figure 7), with the temperature change curve following closely the humidity change for grass. The correlation at more than 0.98 is

highly significant and it shows the responsive physiological reaction of the grass sward to changes in surface temperature (Figure 8).

Similar correlations are obtained for graviola (Figure 6) and for cyclamen (Figure 9).

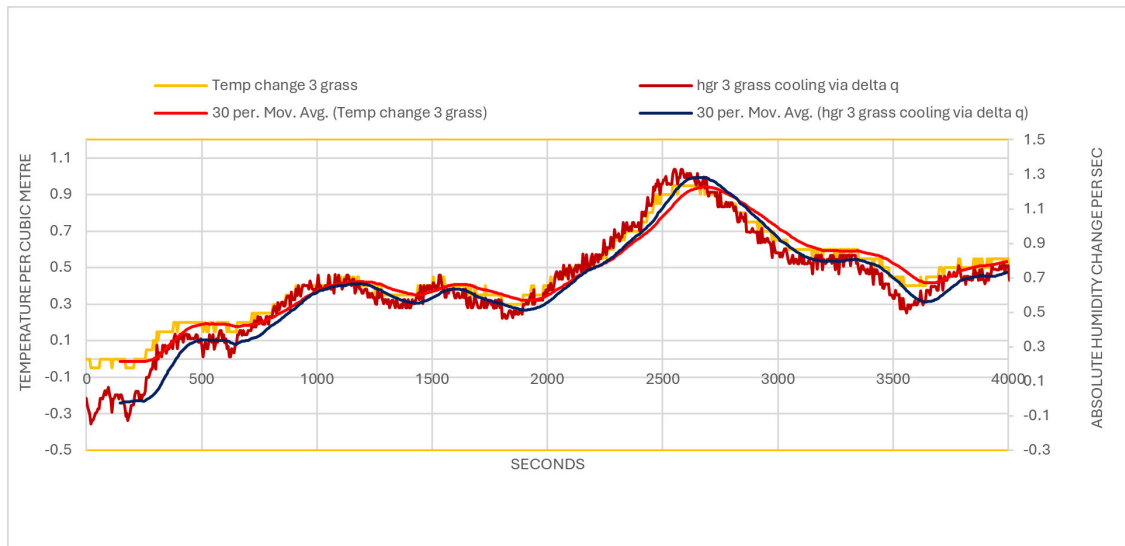


Figure 7. Temperature versus plant surface humidity.

Note: Experiment of 31st July, 2025. The change in surface temperature compared with the change in absolute humidity for grass. For a temperature rise per sec of 0.9 °C, the absolute humidity increased by 1.3 g/m³.

Source: @Peter Bunyard.

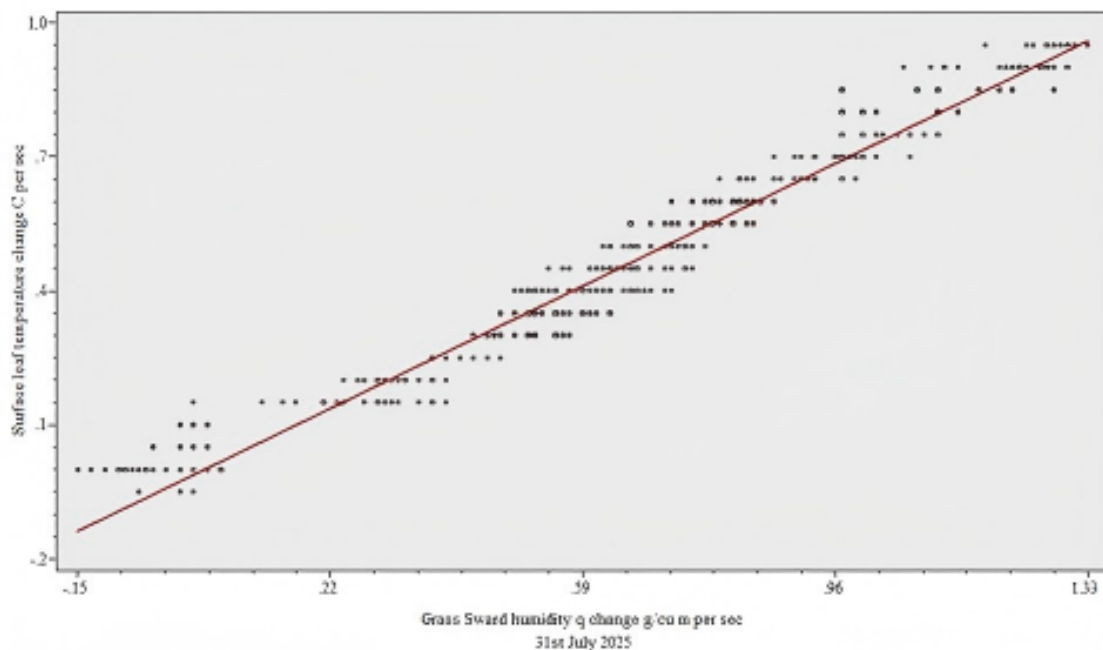


Figure 8. Regression plot: Grass sward vs temperature change.

Note: Experiment 31st July. Correlation of 0.98 for the change in temperature and the absolute humidity change for grass. Tested by linear regression, Pearson's r (Correlation Coefficient) = 0.9817.

Source: @Peter Bunyard.

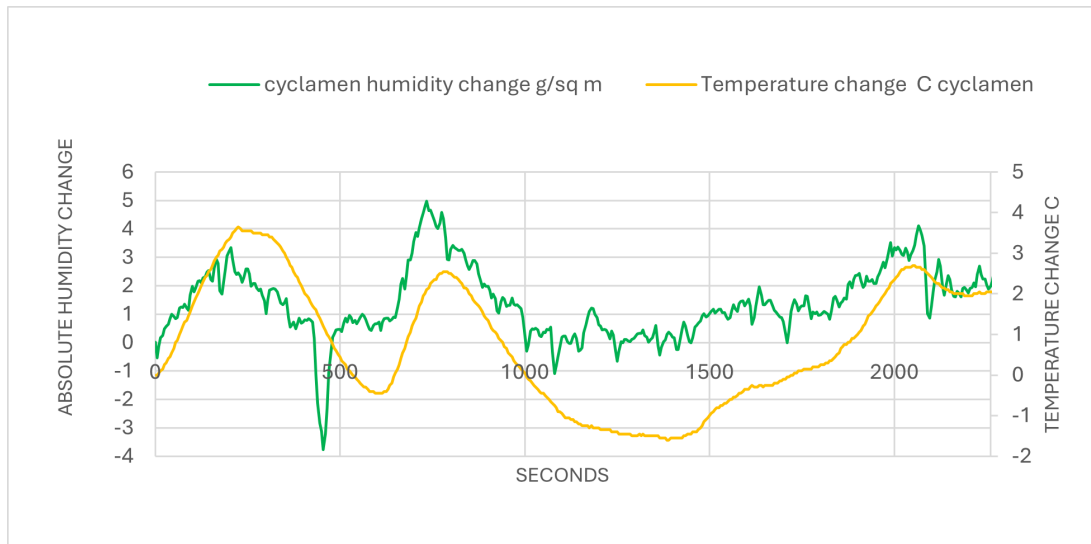


Figure 9. Absolute humidity versus temperature change.

Note: Experiment on May 2nd, 2025. Change in absolute humidity, gm^{-3} of Cyclamen leaf compared to temperature change.
Source: @Peter Bunyard.

Figure 10 shows that the temperature difference and hence, the cooling, between the control and the cyclamen was 22°C , and between the control and graviola was 17°C . **Figure 11** indicates that the cooling of the graviola and cyclamen, as calculated from the absolute humidities of the two specimens and the control, accords well with actual temperature measurements of the specimens and the false grass. Thus, the difference between the 53°C and the calculated cooling of the graviola, namely 18°C , gives a surface temperature of 35°C , and close to that measured at 34°C , and the difference for the calculated cooling of the cyclamen, namely 22°C , makes for a surface temperature of 31°C , as was measured.

The ability of vegetation to cool leaves to an optimum temperature is well exemplified in the experiment on May 15th, 2025, involving both cyclamen, grass, and the tropical tree, graviola. Furthermore, the results indicate that the graviola maintains a higher surface temperature than cyclamen and grass, while all three samples keep their surface temperatures below that of the control. The isolation on the 15th May in the conservatory was 480 W per square metre, and the temperature of the false grass was 53°C . The control showed a surface temperature of 37°C , the graviola a surface temperature of 34°C , the grass 33°C , and the cyclamen 31°C (**Figure 11**).

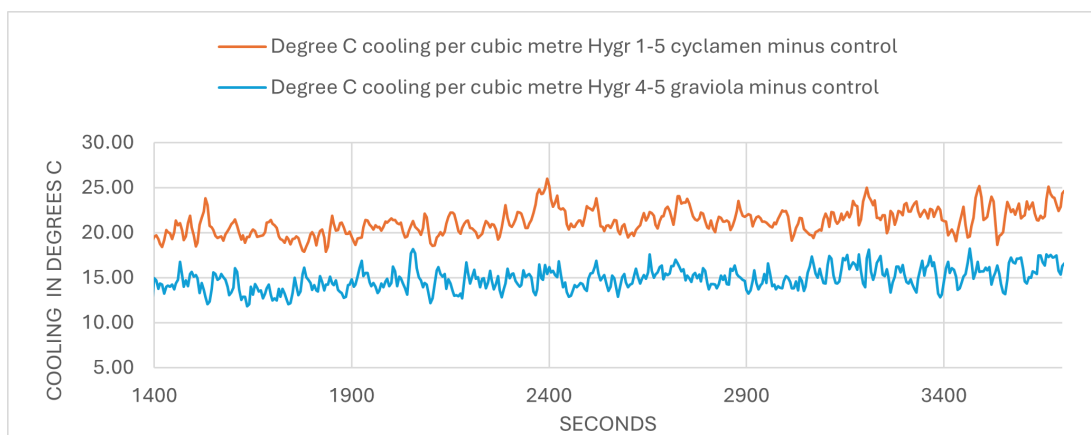


Figure 10. Cooling per kg of air per sec.

Note: Experiment of May 15th, 2025. The surface cooling of the graviola and cyclamen is derived from the absolute humidities of the specimens minus that of the control and converted via Latent Heat calculations to calculated cooling.
Source: @Peter Bunyard.

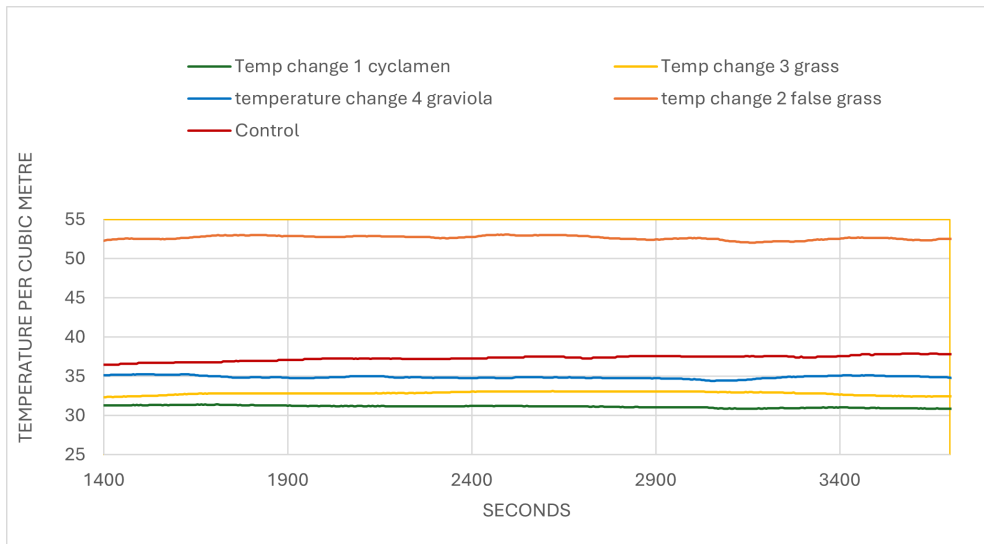


Figure 11. Temperature per cubic metre per sec.

Note: Experiment of May 15th, 2025. The surface temperatures. The vegetation samples have regulated their temperatures to be below that of the ambient air (control).
Source: @Peter Bunyard.

The close correspondence between the actual temperatures of the vegetation samples, as measured with the hygrometers, and the calculated surface temperatures using the physics of ideal gases (Equations 1–11), provides evidence of the integrity of the experiments with respect to the ability of plants to thermoregulate their surface temperatures by means of regulating their rates of transpiration.

Figure 12 shows peak surface temperatures from 17 experiments for false turf, graviola, cyclamen, grass, and

the control ambient air. On cloudy days, the vegetation samples maintain a surface temperature higher than that of the ambient temperature. The reverse is true for hot sunny days, during which the vegetation in general keeps its surface cooler than the ambient temperature. Thus, in general, the vegetation maintains a temperature below that of the ambient air when the latter is above 35 °C and a higher vegetation temperature than the ambient air when the latter is 20 °C and below.

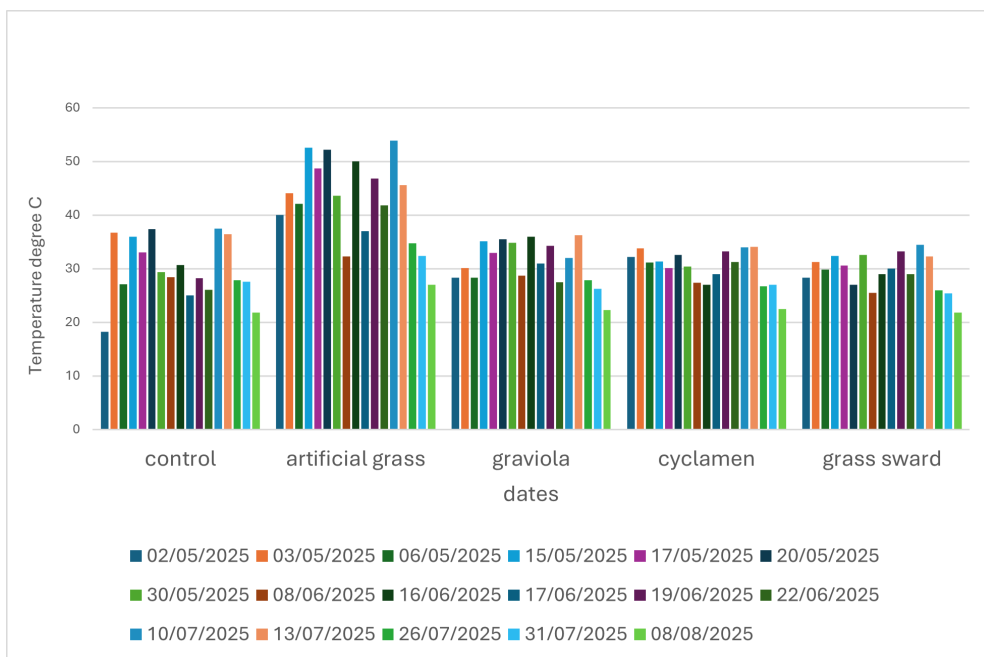


Figure 12. Surface temperatures.

Note: Comparable surface temperatures under differing conditions for the control, artificial grass, graviola, cyclamen, and the grass sward.
Source: @Peter Bunyard.

4. Discussion

The experimental evidence presented here reveals thermoregulation as a characteristic operating across multiple spatial and temporal scales. At the molecular level, stomatal apertures respond to temperature changes within seconds. This leaf-level regulation, when aggregated across forest canopies, creates measurable microclimate effects. At the regional scale, the collective transpiration drives cloud formation and precipitation patterns. Continental-scale effects emerge through the biotic pump mechanism, whereby pressure gradients generated by forest transpiration draw moisture from coastal regions deep into the interior^[7–12]. Ultimately, these processes contribute to planetary-scale climate regulation through latent heat transport beyond the reach of surface greenhouse gases. Understanding these nested feedback systems (from stoma to biosphere) is essential for grasping how vegetation actively shapes climate rather than merely responding to it^[12–14].

It becomes clear from the experiments that plant species, with their green leaves and relatively low albedo, have evolved the means to regulate the rate of transpiration to counteract the sensible heat absorbed under direct sunlight. Furthermore, plants take temperature regulation a step further by bringing their surface temperatures close to an optimum for metabolic activities, including photosynthesis. In conclusion, a plant's ability to regulate its transpiration rate in order to control its surface temperature appears to be a characteristic that has evolved for its well-being. Simultaneously, evapotranspiration permits a small percentage of the transpired water vapour to be sufficiently available for photosynthesis.

In a warming world, that connection between total water availability and a plant's ability to cool itself must become a major consideration in terms of selecting crops. Water-use efficiency, by which crops are selected for their parsimony in water use, may have to be reconsidered in the light of evapotranspiration's role in keeping surface temperatures below ambient air temperatures. That being the case, the necessity for productive agriculture in a warming world will be adequate groundwater during the growing season, especially when utilising irrigation^[12–16].

The considerable energy taken up as latent heat, some 2258 joules per gram of water vapour, not only cools the surface but, by being carried to cloud-forming altitudes, passes beyond the impact of the surface greenhouse gases. In con-

sequence, plants, by means of transpiration, not only cool the leaf surface but, in general, they cool the Earth's surface. As global temperatures increase from global warming, and plants react by increasing evapotranspiration, the proportion of latent heat to sensible heat will increase, thereby reducing the Bowen Ratio. Vegetation, therefore, has the capacity to help cool the Earth as the surface warms up because of global warming and the relationship to the anthropogenic emissions of greenhouse gases^[1,2,16].

Cooling by means of evapotranspiration has profound implications for global surface temperatures. In a recently published book, *Cooling the Climate: How to Revive the Biosphere and Cool the Earth within 20 years*, Rob de Laet and Peter Bunyard calculate that over the forested Amazon Basin, as much as 42% of the sunlight, on average, some 240 W per second, is absorbed as latent heat by the transpiring rainforest. The warm vapour, carrying its latent heat with it, rises through the air column and, with the help of bioaerosols, condenses into light-reflecting dense rainclouds^[1–3]. The forming of clouds over the tropical rainforest, plus the export of latent heat energy from evapotranspiration, could result in as much as 80% of the total daily solar input to the Earth's surface being returned to Space, hence close to some 200 W per square metre of the average 240 W per square metre received from the Sun^[1–4].

The latent heat, several kilometres above the Earth's surface, is fully released as the vapour condenses into drops of rain. The energy, now in the form of long-wave electromagnetic infrared radiation, will warm the surrounding air by as much as 2.5 °C per kg of air for each gram of condensed vapour. That air cools as it rises, losing its energy, which ultimately irradiates out to Space. The fact that the upper troposphere has temperatures below –50 °C, not only acts as a cold trap, thereby preventing the loss of water from the planetary surface, but is evidence that the latent heat, released during cloud-forming, rather than remaining trapped, escapes fully to space as electromagnetic radiation^[6,17].

That considerable cooling, which brings about a surface temperature under the canopy of 25 °C, is ideal for plant growth. The forest vegetation also mixes in bioaerosols with the transpired vapour, thereby bringing about enhanced cloud-condensation and the likelihood of rain. The clouds help with the surface cooling by increasing atmospheric reflectivity, and the rain is vital for forest growth deep in the

hinterland^[3,17].

The condensation of vapour brings about a thousand-fold reduction in volume, from 22.4 L (1000 cc/L) to just 18 cm³. To fill the partial vacuum left by the vapour's transformation to liquid, the air from below flows upwards and is replaced by surface air from the same latitude ocean. That flow of surface air brings with it the moisture evaporated from the ocean. In effect, 40 per cent of the rainfall over the Amazon Basin is derived in that way from the tropical Atlantic Ocean, the remaining 60 per cent coming from the multiple recycling of that which has been evapotranspired^[7,8]. Thus, average annual rainfall over the forested Amazon amounts to 2250 millimetres compared to 1370 millimetres of evapotranspiration^[12,15].

The flow of air from the ocean, as a consequence of vegetation-induced cloud-forming over the rainforest, has been described by Anastassia Makarieva and Victor Gorchkov as none other than the *biotic pump*^[7]. Without the rainforest, there would be no biotic pump, and without the biotic pump, the forests deep in the interior of a continent would receive insufficient rainfall for their survival. A

vicious circle will have been engendered. The concern is that the extent of deforestation across the Amazon Basin has brought the forest ecosystems uncomfortably close to the tipping point when the biotic pump fails, and the remaining forest suffers drought and wholesale die-back. Ali bin Shahid, from the 2023–2024 droughts in the Amazon Basin, finds that an annual reduction in rainfall of some 450 millimetres is leading to biotic pump failure^[2]. That is a 20 per cent reduction from the norm and close to half the contribution of the tropical Atlantic Ocean to average rainfall over the forested Amazon^[2,13–16].

Climate models, in which the consequences of widespread deforestation on vegetation are projected, consider that the closed-canopy rainforest will transform into Savannah^[18,19]. Such models fail to account for the action of the rainforest and the biotic pump in bringing in that vital 40 per cent of humidity from the ocean. Application of the physical principles of the biotic pump indicates that widespread deforestation will lead not to savannah but, particularly in the western regions of the Basin, to the most arid of deserts (**Figure 13**)^[7,18].

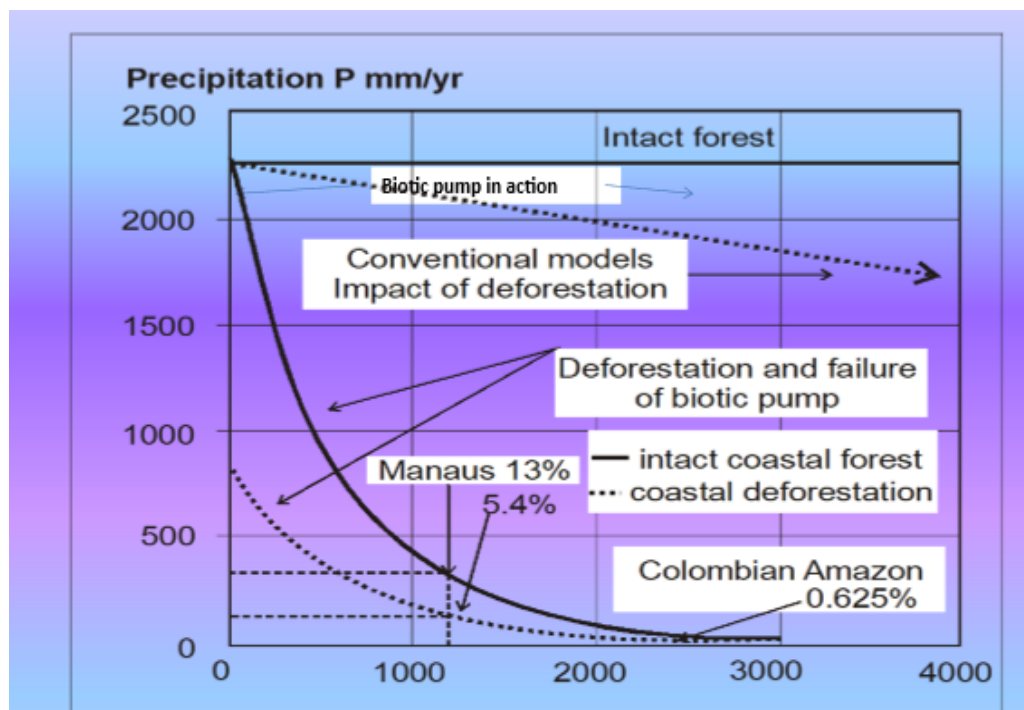


Figure 13. The consequences of widespread deforestation taking biotic pump failure into account^[7].

Note: Deforestation's impact on the biotic pump. Makarieva & Gorchkov (Makarieva A.M., 2007) use a length of 600 km over which distance a molecule of water will evaporate and fall out through precipitation.

$$P_x = P_0 \exp\left[-\frac{x}{l}\right]$$

Source: @Peter Bunyard.

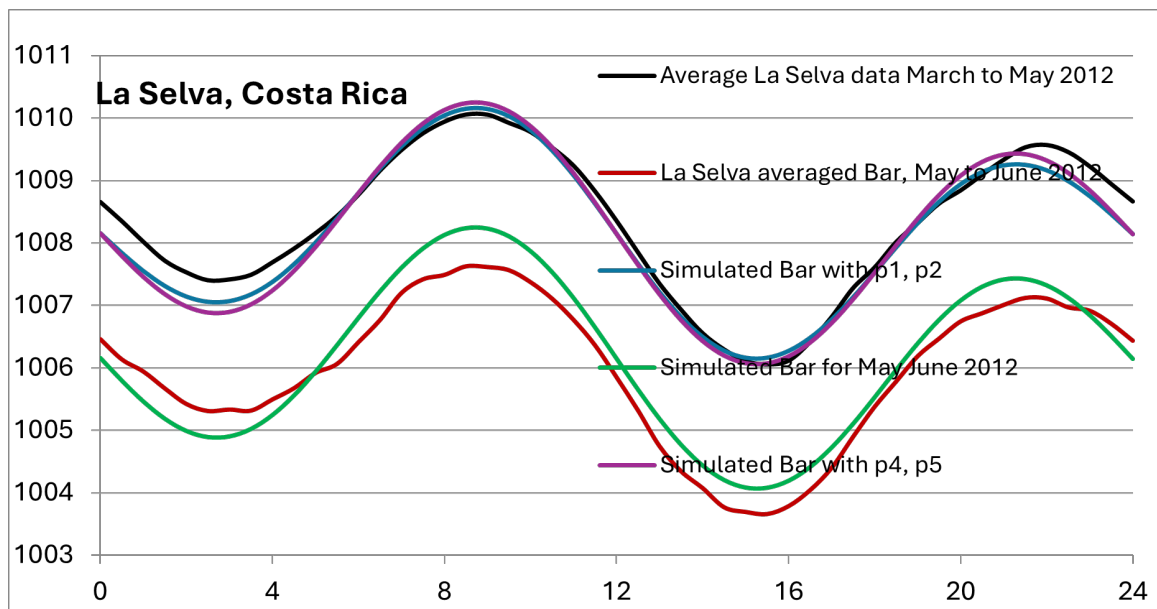
In principle, the biotic pump will function once the rate of transpiration, for instance, from a forest close to the same latitude ocean, has generated a partial pressure reduction from vapour condensation that is sufficient to cause a flow of surface air from the coast to the continental hinterland. The pressure gradient from the ocean to the forested continent is the result of the rate of evaporation per square metre of the same latitude adjoining the ocean being an order of magnitude less than the rate of transpiration. **Figure 1** shows that under bright sunlight, the grass sample has a rate of transpiration, measured by the absolute humidity, that is 15 times greater than the rate of evaporation from the water sample.

Meanwhile, meteorological data from the tropical rainforest of La Selva, Biological Station, in Costa Rica, shows a remarkable daily sinusoidal wave, with a marked pressure reduction in the afternoon, reaching its nadir at 1600 hours (**Figure 14a**). In averaging the meteorological data for a boreal forest in Finland, Jokioinen, Latitude: 60°48'50.44'', Longitude: 23°29'51.40'', Bunyard finds that during the summer months, and in particular September, when the day-length is similar to that of the Tropics, the boreal forest displays (**Figure 14b**) all the characteristics in terms of atmospheric pressure that can be expected for the equatorial

tropics^[20,21]. Finally, (**Figure 14c**), the liquid water path, over the tropical Pacific Ocean, shows a similar sinusoidal fit in the late afternoon, as found for the atmospheric pressure change in the tropical rain forest of La Selva, Costa Rica, and in the boreal forest of Finland in September, when the day-length is similar to that of the equatorial Tropics and the tropical Pacific.

Figure 14 shows that in all three cases that the atmospheric pressure in the late afternoon has reduced significantly. The reduction in pressure causes a measurable airflow which, in the case of the tropical and boreal forest, leads to an influx of humid air from the same latitude ocean to fill the partial vacuum as vapour condenses. Should deforestation cause a decline in the rate of transpiration, that will reflect in a reduced sinusoidal wave and, in consequence, a likely reduction in the surface airflow from ocean to continent^[20,21].

Severe drought, as occurred over the Amazon Basin in 2005, 2010, 2023, and 2024, challenges the capacity of the rainforest trees to transpire at a rate that can maintain the surface temperature at a level optimum for growth and even survival. Moreover, once the rate of transpiration falls below a critical level, the biotic pump will falter and even fail. That then potentially becomes a death-blow for the surviving rainforests deep in the continental interior^[2].

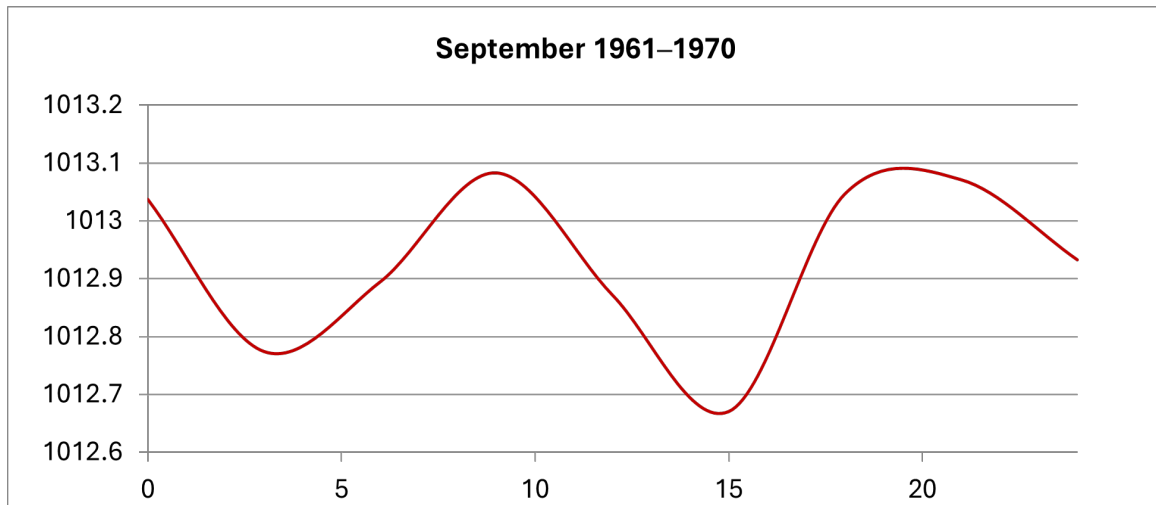


(a) Double sinusoidal wave for the average daily barometric pressure, La Selva Biological Station, Costa Rica.

Note: The phenomenon of the barometric pressure wave showing the actual pressure wave and the simulated close-fitting curve for La Selva, Costa Rica. Source: Plamen Natchev & Peter Bunyard^[20]. The formula, developed by Natchev, used coefficients, p_{1-5} , to simulate the actual form of the wave with its sinusoidal pressure change.

$$\text{Bar pressure } p = p_0 + (p_1 - p_2 \cos(\frac{\pi t}{12})) * \sin(\frac{\pi t}{12})$$

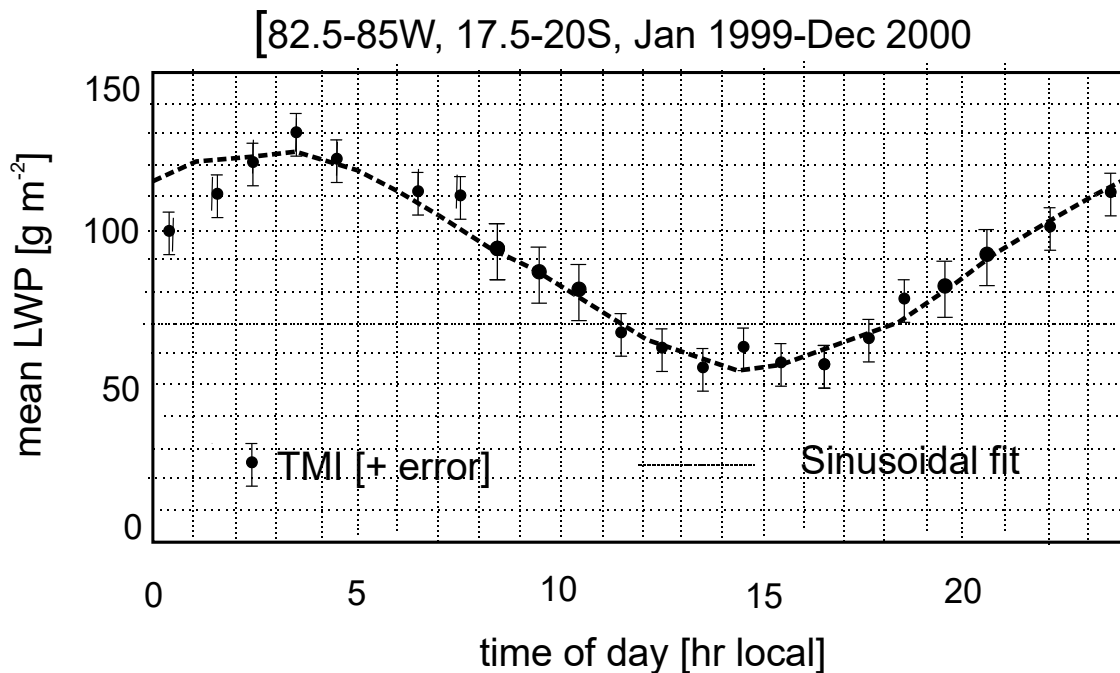
Figure 14. Cont.



(b) Double sinusoidal wave for the average daily barometric pressure, September, for Jokioinen, Finland.

Note: Y-axis, the averaged barometric pressure for September (12 hours daylight) between 1961–1970, for Jokioinen, Finland, takes the same double sinusoidal form as that for an equatorial rainforest such as La Selva in Costa Rica, **Figure 14a** ^[20].

Source: @Peter Bunyard.



(c) Sinusoidal wave for the average Liquid Water Path, Pacific Ocean.

Note: Atmospheric liquid water path as determined over 24 hours in the Pacific reveals similarities with the cosine component derived from the barometric wave for La Selva, implying that the diurnal wave is strongly influenced by hydrology.

Source: Wood, Bretherton, & Hartmann ^[21].

Figure 14. Phenomenon of the barometric tidal wave.

In that respect, Anastassia Makarieva and Victor Gorschkov showed in their original 2007 paper that the precipitation inland over river basins that were forested re-

mained as high, if not higher than at the coast, whereas the rainfall over deforested basins showed an exponential decline from the coast to the hinterland (**Figure 15**) ^[7].

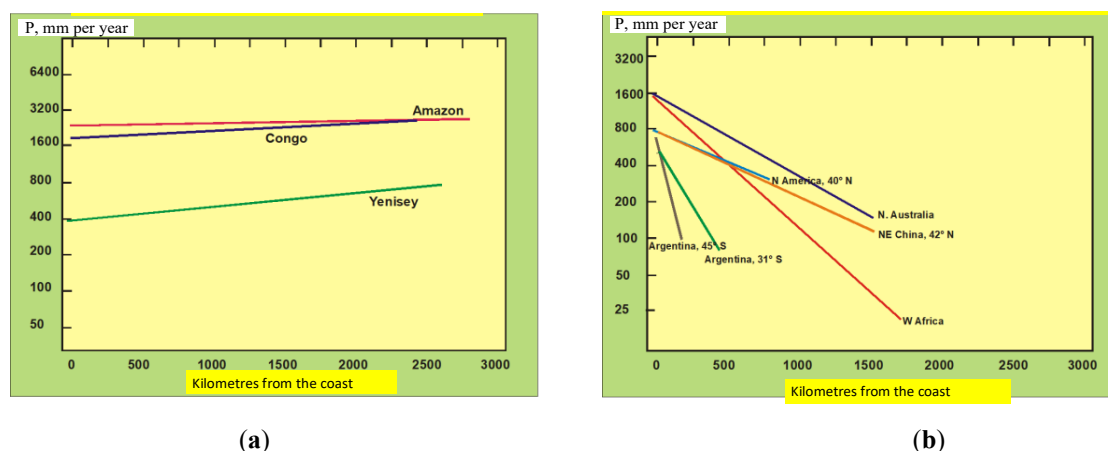


Figure 15. Forest and continental rainfall^[11]: (a) Left, precipitation over forested river basins; (b) Right, precipitation over river basins without forest.

Source: Makarieva, A., Gorshkov, V., 2007. Biotic Pump of Atmospheric Moisture as Driver of the Hydrological Cycle on Land. *Hydrology and Earth System Sciences*. 11(2), 1013–1033.^[7]

5. Conclusions

One hundred million years ago came the evolution of the angiosperm flowering plants. With their broad, vascularised leaves, angiosperm trees could transpire at a rate four times greater than gymnosperms and more ancient forms. As Boyce, Benton et al. from the Missouri Botanical Gardens, point out^[22–25], evolution enabled the forests to penetrate deep into continents and therefore far from the coastal source of rainwater. Salati's discovery that rainforests recycle more than 60 per cent of rainfall every 600 kilometres across the Amazon Basin, from East to West, with the necessary make-up of humidity from the ocean, indicates the prime importance of the closed-canopy rainforest in the adequate watering of the continental interior^[8]. Thus, the evolutionary impact of the angiosperms was to enhance cloud-forming and permit the realisation of the biotic pump. With a functioning biotic pump came the inevitable colonisation of the post-Pangea tectonically-formed continents and the spread of forests^[22–25].

Average surface temperatures at that time in evolutionary history were 7 °C warmer compared with 250 years ago, and the CO₂ concentrations in the atmosphere were at least 7-fold those of today. Clearly, the spread of such forests over the continental hinterland would have absorbed CO₂ in forming biomass, and the geological record indicates that the concentration of that greenhouse gas reduced from some 2000 parts per million, 60 million years ago, to just 280 ppm at the dawn of the industrial era, 250 years ago^[26–28]. While

the reduction in CO₂ was exponential, tailing off some 20 million years ago, the temperature reduction followed a linear trajectory, albeit with impacts, such as the Chicxulub asteroid. Some 20 million years ago, when CO₂ concentration had tailed off, the average surface temperature was still 2.5 °C warmer than today^[27].

The divergence between CO₂ concentration (which declined exponentially) and temperature (which declined linearly) suggests that factors beyond CO₂ reduction contributed to planetary cooling. The latent heat transport engendered by closed-canopy rainforests represents an energy flux 200 times greater than that involved in photosynthetic CO₂ uptake^[1,25–29]. Given that contemporary rainforest canopy temperatures (~30 °C) align with the optimal thermoregulatory set-points observed in the experiments^[25–29], the evolution and spread of angiosperm rainforests likely contributed significantly to both surface cooling and atmospheric CO₂ reduction through complementary mechanisms. The subsequent formation of glaciers and polar ice, with their high albedo, brought on by the millennial cooling, further amplified the process of cooling over the past 18 million years (**Figure 16**).

It therefore seems reasonable that the evolution of the angiosperm rainforests was a major factor both in the surface cooling and in bringing about a significant reduction in atmospheric CO₂. That being the case, the efficient transpiration-cooling of the rainforests will have helped bring about glaciation across the planet. As pointed out by Lovelock^[30], a planet with widespread forests and glaciers tempers the climate and confers relative climate stability.

In conclusion, the great rainforests of the world have contributed to the planet having surface temperatures that, historically, have been close to ideal for the elaboration of human societies and agriculture. The swiftest and safest way to cool the Earth is for mankind to work together to regenerate those forests of the world that have been destroyed over the past century. Bunyard and de Laet calculate that the current

global warming of 1.5 °C could be reduced to less than 1 °C by regenerating tropical rainforests over 2.5 million square kilometres, hence equivalent to the rainforests that have been destroyed over the past 70 years. Hence, regeneration will have a cooling impact equal to the current global warming and, as an added bonus, will absorb vast quantities of CO₂ in the form of biomass and natural carbon sinks^[1,2,29,30].

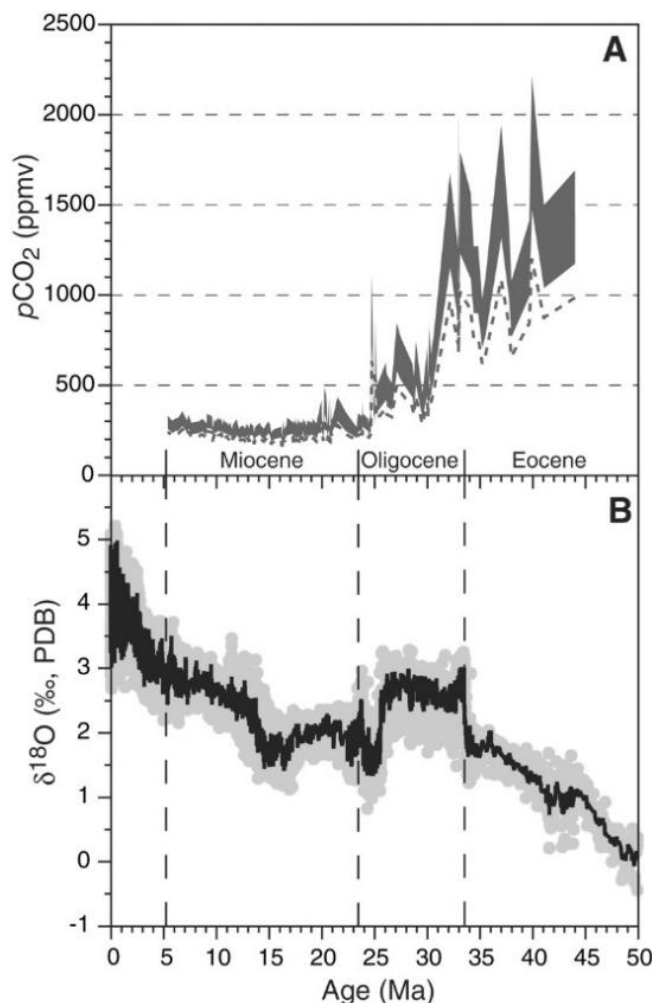


Figure 16. Original graph by Pagani et al. 2005^[28].

Note: The Y-axis shows the exponential reduction in CO₂ over the past 50 million years.

The global average surface temperature showed a linear reduction from 6 °C 50 million years ago compared to the pre-industrial temperature of 250 years ago^[27,28].

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Informed Consent Statement

Not applicable.

Institutional Review Board Statement

Not applicable.

Data Availability Statement

If required, the experimental results as described would be available by contacting Peter Bunyard, email: peter.bun-

yard@btinternet.com.

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Conflicts of Interest

The author declares no conflict of interest.

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