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RAINFALL PATTERNS AND AGRICULTURAL PRACTICES

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ABSTRACT

A mechanism is proposed to account for the observed rainfall increases over forests compared to geographically similar non-forest areas. This mechanism is based on the "thermal mountain" concept advanced by Malkus and Stern in 1953. A 10 km long forest, 6°C hotter than the surrounding region, can produce a thermal mountain 1026 meters high.

The height of the thermal mountain is dependent on the prevailing windspeed, the temperature difference between the forest and the surrounding area, the absolute air temperature, and the length of the forest in the direction of the prevailing wind.

The extensive deforestation due to agricultural needs may have profound effects on the climate, especially rainfall patterns, of the farm lands and surrounding countryside.

Introduction

One aspect of food production that unfortunately has been little studied has been the deforestation attendent with the growth of agriculture. Deforestation has many measurable environmental effects of which increased erosion and precipitation runoff have been most studied [1, 2]. Deforestation, however, may also seriously affect the climate and, in particular, the rainfall.

It has long been suggested that forests exert some influence on local climate. Observations have indicated that rainfall is greater over forested areas than over nearby, geographically similar, but non-forested areas [3]. Meteorological stations in many countries, including India, Russia, France, Sweden, and the United States have recorded up to 25 per cent greater rainfall over forests than over fields [4].

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Two theories have traditionally been proposed to explain this phenomenon. The first, taking advantage of the original observations that air is cooler over forests than over fields, is that the forests obstruct the air flow causing the air to pile up, cool and precipitate a portion of its moisture. Proponents of the second theory suggest that the increase in rainfall is due to the higher transpiration rates of forests and consequently greater atmospheric humidity.

The present paper points out inconsistencies inherent in these theories and proposes a new mechanism based on the albedo[1] differences between forests and fields.

Previous Work

Observations of increased rainfall over forests have been reported in the literature since the middle of the nineteenth century. While some of these reports are unsubstantiated observations, many are based on actual rainfall measurements.

Blodget, in his Climatology of the United States, was perhaps the first researcher in the United States to report that precipitation over forest areas was greater than over fields [5]. Blanford, reporting a similar phenomenon for the forests of India, computed that the average annual rainfall was 12 per cent greater over forests than over open fields [6]. Ferdinand V. Hayden, U. S. Geologist, in the report of the Commissioner of the General Land Office of 1867, suggested that the planting of trees in the Great Plains would increase the rainfall and distribute it more evenly throughout the year [7]. He cited as evidence " . . . the increase of the timber have (sic) already changed for the better the climate of that portion of Nebraska lying along the Missouri, so that within the last twelve or fourteen years the rain has gradually increased in quantity and is more equally distributed through the year."

The United States Timber Culture Act, passed in 1873, attempted to promote Hayden's theory by encouraging the growth of timber on the plains and prairies of the Great American Desert. The act did not provide adequate incentives for the farmers to plant trees and met with little success [8].

Raphael Zon, in the final report of the National Waterways Commission in 1912, presented one of the most comprehensive summaries of the data gathered on the subject of increased rainfall over forests. He attempted to present "the well established scientific facts in regard to the relation of forests to water supply." After

[1] Per cent reflectivity of solar radiation.

reviewing numerous reports, Zon concluded that the excess of precipitation over forests, while not universally conclusive, usually varies from one per cent to over 25 per cent.

Rudolph Gieger, in The Climate Near the Ground, provides a short review of the subject of rainfall changes due to forests [9]. He cites and dismisses a number of reports detailing rainfall anomalies in areas that have undergone deforestation. "Precipitation formation is, however, a process that takes place in the upper atmosphere, and it is very unlikely that the types of ground below will have any significant effect on it." [9, p. 365] Researchers have now realized that surface formations can influence and sometimes dictate weather patterns [10, 11].

George H. T. Kimball reported precipitation changes in a 7000 acre area in the Cooper Basin of Tennessee that had been denuded by smelting operations [3]. The forested area surrounding the denuded area receives 28 per cent more rain annually.

Recently, the corollary to these observations has been reported by W. M. Warren [12]. He related the progressively lower rainfall of the Ranchi Plateau in India to the widespread deforestation during the years 1904-1932. Using data from meteorological stations, Warren reported a statistically significant drop in the number of rainy days during the dry season (January-June); -1.8 days in May (highly significant) and -1.7 days in June (not significant). A drop was also found in the amount of rain falling during the same period; -2.44 cms. in May (significant) and -4.22 cms. in June (nearly significant).

The abundance of evidence indicating increased rainfall over forests has prompted researchers to propose various hypotheses to explain the phenomenon. One of the first was reported by Hayden in 1867: "(Babinet lectured) . . . a few years ago it never rained in Lower Egypt. The constant North winds which almost exclusively prevail there, passed without obstruction over a surface bare of vegetation; but since the making of plantations an obstacle has been created which retards the current of air from the north. The air thus checked accumulates, dilutes, cools and yields rain."

Zon, referring to rainfall differences over forest pastures and treeless regions, noted, "The great excess of precipitation over the forest during fall and winter when the clouds are very low is no doubt the result of condensation due chiefly to the mechanical obstruction offered to the moisture laden air." [14] A necessary component of this theory is that the forest cools the air in addition to obstructing it in order to lower the condensation point. "(It rains . . . due to the dampening and chilling effect of the forest upon the atmosphere, which induces a greater condensation of water vapor."

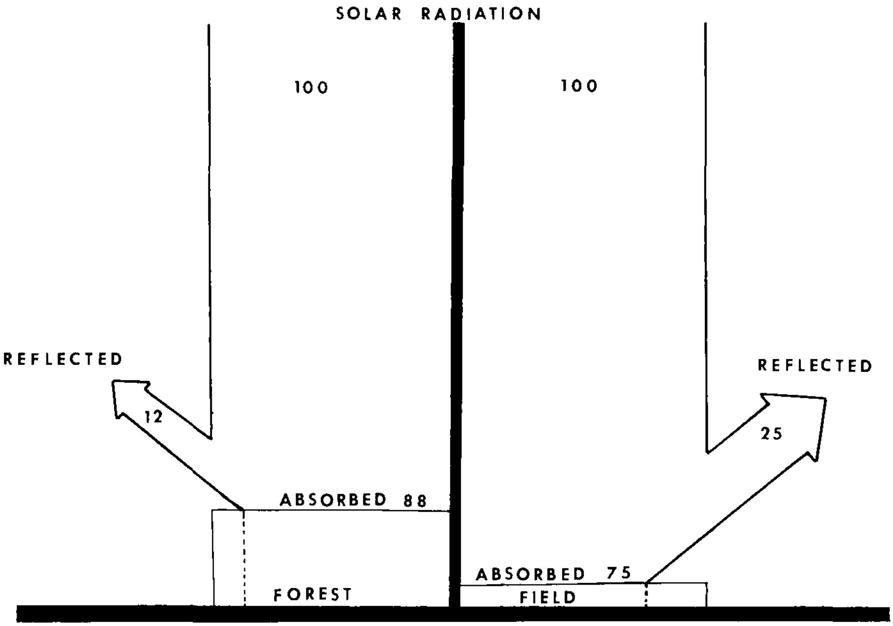

Figure 1. Albedo and sensible heat flux of forests and fields.
The absorbed solar energy that is not used for photosynthesis is converted to heat by the vegetation and is used to evaporate water and to raise the temperature of the leaf surfaces. This in turn raises the temperature of the air. Forests absorb more sunlight and so heat the air more than do fields.

[4] Mere obstruction, unless it forces moving air upward, will not produce any sizable amount of precipitation [13, 14]. Recent investigations, contrary to earlier observations, have shown that the air over forests is substantially hotter than the air over fields. This is due to the lower albedo (per cent reflectivity of solar radiation) of forests (see Figure 1). More solar radiation is absorbed and converted to sensible heat (heat that actually raises the temperature of the absorbing surface) which heats the air over the forest [15, 16]. Thus forests, by heating the air, actually raise instead of lower the saturation point. Zon's obstruction hypothesis then, cannot alone account for the increased rainfall over forests.

Zon also suggested that the large amount of water transpired by forests would so increase atmospheric moisture that increased precipitation would be inevitable [4]. Federov and others have conducted studies indicating that forests do indeed transpire more water than adjacent fields [17]. Recent reports suggest, however, that Federov may have been wrong. While forests do absorb more solar radiation than open fields, less of this energy is used to transpire water [16]. The excess energy is converted to sensible heat, raising the temperature of the air over the forest. The transpiration rates of forests do not seem to be consistently higher than those of open fields and may in fact be substantially lower [15]. Lower transpiration rates and warmer air would serve to lower the relative humidity over forests, not to raise it. Thus, the high transpiration rate theory cannot explain the excess rainfall over forests.

Proposed Mechanism

The present paper proposes a mechanism to account for the observed rainfall increases over forests. This mechanism is based on the thermal mountain concept advanced by Malkus and Stern [18]. Malkus and Stern constructed a mathematical model of the formation of clouds over flat islands. Such islands, when heated by the sun, become warmer than the surrounding water. The air over the island is then heated and rises, creating a thermal mountain. When winds blow over the island this thermal mountain functions as the exact equivalent of an orographic mountain resulting in the Föhn effect [11]. The air is forced upward where it cools and forces condensation of a part of the water vapor carried [19, 20]. The mathematical model developed by Malkus and Stern, of cloud production over heated areas, was subsequently supported by observations of cloud formation over Puerto Rico and Nantucket [21].

Black and Tarmy used this same model to study the possible effects of coating large areas with asphalt [22]. Such a coating could lower the albedo and create an area more than 5°C hotter than the surrounding regions. They calculated that an asphalt strip 30 kms long could produce a thermal mountain 900 meters high, assuming typical local meteorological conditions (Eastern Libia).

The corollary of Malkus and Stern's thermal mountain concept was used by Otterman to support a hypothesis for the creation of deserts by denuding of marginal semi-arid lands [23]. According to Otterman, overgrazing marginal lands raises the albedo of those areas due to the exposure of the high albedo soils. The decreased absorption (greater reflection) of solar radiation would tend to make the areas of exposed soil cooler than those covered with vegetation. The cool area is then the reverse of the Malkus/Stern thermal mountain. Air will sink instead of rise when passing over such an area and there is consequently less cloud formation and rainfall [23].

There are several problems with this hypotheses. It obviously does not apply to areas with low albedo soils. In addition, when comparing bare soil to vegetation, albedo is not always inversely correlated to sensible heat flux (temperature over the surface). That is, a part of the solar radiation absorbed by plants is used for evapotranspiration and does not raise the temperature of the vegetation [15, 24]. This, of course, is not the case with bare, dry soil.

A good correlation does exist between albedo and temperature when comparing two types of vegetation, especially forest to field [15]. Brown measured a sixty-two-year-old stand of Black Spruce *(Picea mariana)* and an adjacent clearcut strip for both albedo and sensible heat flux [16]. The Spruce stand had an albedo between 14 and 20 per cent lower than the clearcut strip and was between 4 and 7°C warmer during the day and 2.5°C warmer at night.

This temperature differential compares favorably with that used by Black and Tarmy in their thermal mountain calculations [22]. The Spruce stand could act in much the same way as Malkus and Stern's heated island and Black and Tarmy's asphalt strips, creating a thermal mountain that could increase cloud formation and rainfall [18]. Monteith established that crops have an average albedo of 25 per cent [25]. The published values of the albedo of forests are almost universally lower than 25 per cent (see Table 1). These albedo differences should give rise to temperature differentials between many varied forest lands and field and croplands. The model, therefore, should have wide applications.

CALCULATION OF A FOREST-CREATED THERMAL MOUNTAIN

The mathematical model of an airflow over a heated area, developed by Malkus and Stern results in a set of four simultaneous differential equations [18]. These, in turn, can be divided into two additive parts. The first defines the boundary condition and is of little importance to the present study. The second part, however, models the airflow over the heated area at altitudes important to cloud formation and rainfall. The airflow patterns predicted by this model are the same as those created by orographic mountains and are called thermal mountains [22].

The size of the thermal mountain that could be created by an area that is hotter than the surrounding regions is dependent on four variables: the temperature differential of the heated area, t, the length of the hotter area (in the direction of the prevailing wind), L, the prevailing wind speed, u, and the temperature gradients in the air.

Table 1. The Albedos of Various Surfaces

Reflecting Surface	*Albedo (%)*	*Source*
Natural Meadow on dry subsoil	22	a, f, g
Grass, dense and deep green	30	a, g
Rye, in various stages of development	18-20	a
Winter wheat, in various stages of development	15-20	a
Summer wheat, in various stages of development	10-25	a
Oats, in various stages of development	18-28	a
Radishes	21-24	e
Potatoes	27	a
Tomatoes	21-22	e
Lupin	28	a
Alfalfa	22	b
Pure, dry Savanna	22	c
Oak Forest	12-18	b, d
Spruce Forest	5-9	b
Tropical Rain Forest	13	c
Mangrove and Fresh Water Swamps	12	c

Sources: a. (29); b. (15); c. (24); d. (30); e. (31); f. (32); g. (33); h. (34).

These are related by the following equations where M is the height of the thermal mountain at any distance x from edge of the heated area.

$$M = \frac{t}{sTm} \begin{cases} 0 & x < 0 \\ 1 - e^{-x\,(k/u)\,(gs/u^2)} & 0 \leqslant x \leqslant L \\ e^{-x\,(k/u)\,(gs/u^2)} \cdot \left(e^{L\,(k/u)\,(gs/u^2)} - 1\right) & x \geqslant L \end{cases}$$

for $(gs/u^2)^{1/2} \cdot (k/u) < 1/2$.

Where $(gs/u^2)^{1/2} \cdot (k/u) > 1/2$

$$M = \begin{cases} 0 & x < 0 \\ \dfrac{t}{sTm} & 0 \leqslant x \leqslant L \\ 0 & x \geqslant L \end{cases}$$

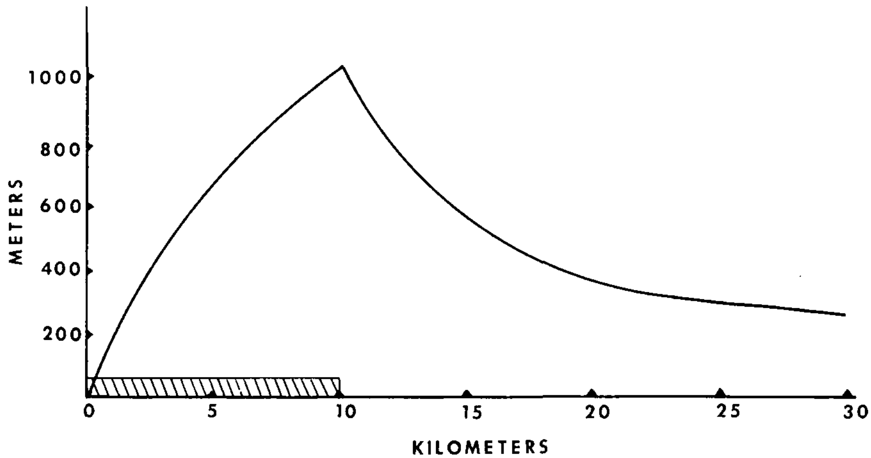

Figure 2. The thermal mountain created by a Black Spruce forest during the day. The forest (shaded area) is 6°C hotter than the surrounding area. The following meteorological conditions were used; wind speed, 3.25 m/sec., absolute air temperature, 300°K; mixing length (k/u); 499.87.

Where: t, temperature increase of the area; s, stability; Tm, average absolute air temperature; k, eddy diffusivity of the air stream; u, wind speed; L, length of the heated area parallel to the wind direction; e, base of the natural logarithm; g, gravitational constant.

Figure 2 represents the thermal mountain calculated for a Black Spruce forest 6°C hotter than its surroundings and 10 Km long. The 6°C temperature differential is typical of the Spruce forest studied by Brown [16]. The maximum height of the mountain is 1026 meters high at the leeward edge of the forest.

Figure 3 represents the thermal mountain created by the same Spruce forest at night when the temperature differential has fallen to 2.5°C. The temperature differential and hence the height of the thermal mountain will change from day to day depending on the insolation received. The thermal mountain shown is 427.5 meters high. The prevailing wind speed in figures 2 and 3 is 3.25 meters per second.

These thermal mountains were constructed from a computer model using the following assumptions.

1. Steady state of all values of variables;
2. additional heat supplied by the area is dissipated in the airflow;
3. unidirectional, uniform wind velocity approaching the heated area;

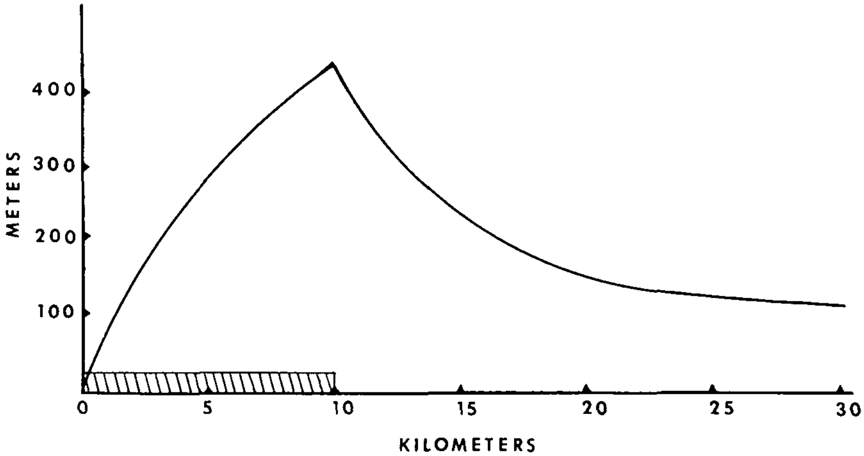

Figure 3. The thermal mountain created by a Black Spruce forest during the night with a temperature of 2.5°C hotter than the surrounding area. The same meterological conditions as Figure 2 were used.

4. the total energy of the circulation system is much greater than the additional energy supplied by the increased temperature;
5. uniform temperature windward and leeward;
6. uniform temperature profile in the heated area;
7. uniform temperature gradient in undisturbed air;
8. the heated area is relatively wide perpendicular to the wind direction; and
9. air is perfect gas.

Conclusion

This paper proposes that a forest, surrounded by a higher albedo area, can create a thermal mountain. The size of this thermal mountain is dependent on four variables:

1. The temperature differential between the forest and the surrounding area;
2. the length of the forest in the direction of the prevailing wind;
3. the prevailing wind speed; and
4. the temperature gradients in the air.

Black and Tarmy analyzed the importance of these factors in the creation of a 900-meter high thermal mountain [22]. They conclude that the length of the hotter area needed to produce this mountain is:

1. Directly proportional to the square of the wind speed;
2. inversely proportional to the mixing length (k/u);
3. sensitive to the temperature differential only when this is outside the practical range of 4 to 8.3°C;
4. sensitive to stabilities greater than 2 x 10*7 cm^{-1} (with a temperature differential of 5°C).

These same conditions apply to the proposed thermal mountains created by forests.

A thermal mountain created in this manner would lead to increased rainfall in the same manner as an orographic mountain and would account for the meteorological data indicating greater rainfall over forest areas than over similar but nonforest areas. The actual increase in rainfall produced by thermal mountains is best calculated by a study of similar orographic mountains with comparable meteorological conditions [22].

If this mechanism is valid it may have far-reaching implications. Man, throughout the ages, has deforested wide-spread areas for both agricultural and timber operations [26, 27]. This deforestation is continuing due to the rapid expansion of our cities and agricultural lands [28]. Small scale deforestation may affect the local climate of agricultural areas through the loss of the thermal mountain and/or the creation of thermal valleys. The attendant changes in rainfall may affect food production and contribute to the increasing desertification of agricultural lands.

Large scale deforestation may affect the energy balance of the entire world and influence the Global climate system. The possibility is raised that man, primitive and modern, has modified climate to a much greater degree than previously thought possible. It seems wise, in this light, to closely monitor the rapid expansion of agricultural lands prompted by the food needs of an increasing population.

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