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THE ENERGY BUDGET AT THE EARTH'S SURFACE: PRELIMINARY WIND TUNNEL STUDIES OF THE PHOTOSYNTHESIS AND TRANSPIRATION OF FORAGE STANDS

Contribution by:

L. A. Hunt, I. I. Impens and E. R. Lemon

INTERIM REPORT

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INTERIM REPORT

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Prepared by

L. A. Hunt, I. I. Impens and E. R. Lemon

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Northeast Branch
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In Cooperation With

N. Y. State College of Agriculture
Cornell University
Ithaca, New York

For

U. S. Army Electronics Command
Atmospheric Sciences Laboratory, Research Division
Fort Huachuca, Arizona

PRELIMINARY WIND TUNNEL STUDIES OF THE PHOTOSYNTHESIS AND TRANSPIRATION OF FORAGE STANDS[1]

L. A. Hunt, Ivan I. Impens and E. R. Lemon[2]

ABSTRACT

Vegetative stands of alfalfa and orchardgrass, grown in flats in a glasshouse, were investigated in a small wind tunnel. The windspeed parameters of the crop surfaces were determined at low radiation intensity at each of two windspeeds; and the rates of net photosynthesis and evapotranspiration were measured at the two windspeeds at each of three radiation intensities.

The roughness length (z_o) increased with windspeed and was greater in orchardgrass. Rate of net photosynthesis, but not evapotranspiration, also increased with windspeed. In consequence, water-use was most efficient under the highest wind regime. The rate of net photosynthesis increased to the intermediate radiation intensity, whereas evapotranspiration increased and water-use efficiency decreased to the highest radiation regime.

The work indicated that a small wind tunnel of the type described would be useful for further studies of the photosynthesis and transpiration of forage stands.

INTRODUCTION

Individual leaves and shoots have been used in many indoor studies of the effects of wind velocity on photosynthesis (22) and transpiration (12). In one study with shoots of Myrica rubra (24), for example, transpiration increased with windspeeds from 0 to 4 m sec^{-1} in the dark, but decreased with windspeeds from 0 to 1 m sec^{-1} under certain conditions of illumination. On the other hand, communities of plants have been used less frequently in indoor studies. Jensen (10) described wind tunnel tests in which the evapotranspiration of a mixed stand of grasses and clovers increased with windspeeds from 2.0 to 20.0 m sec^{-1} under incandescent lamps; and Wadsworth (20, 21) reported wind tunnel studies of dry matter accumulation by young, open stands of barley, pea, and rape growing either in sand or in water under natural illumination. There appear to have been no wind tunnel investigations of the photosynthesis and transpiration of stands exposed to different windspeeds under contrasting radiation loads. The present study was undertaken to provide information on the possibility of using a small wind tunnel to obtain such data for forage stands.

ERRATA SHEET

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Page 9; Paragraph 4; line 1	$P < 0.05$
Page 11, Paragraph 3; line 5	3.0×10^{-2}
Page 12; Paragraph 1; line 1	15.0×10^{-2}
Page 12; Paragraph 1; line 2	$4.0 - 6.0 \times 10^{-2}$

Fig. 2. The CO_2 profiles for orchardgrass, M and L radiation regimes, are in reverse. The two CO_2 profiles marked M are correctly L and the two CO_2 profiles marked L are correctly M.

Table 1. (Corrected) See correct table enclosed.

Table 1. Wind profile parameters, net photosynthesis, and evapotranspiration for alfalfa and orchardgrass stands in a wind tunnel.

Crop or treatment	Roughness length	Displacement length	Net photosynthesis		Evapotranspiration		Efficiency of water use
	$(z_o)^1$	$(d)^1$	$(P_N)^1$	$(\lambda P_N)^1$	$(E_t)^1$	$(\lambda E_t)^1$	$(\lambda P_N/\lambda E_t)^1$
	cm	cm	mg dm^{-2} hr^{-1}	cal dm^{-2} hr^{-1}	mg dm^{-2} hr^{-1}	cal dm^{-2} hr^{-1}	10^{-2}
Alfalfa	1.5 b	5.6a	45a	108a	3,330a	1,948a	5.5a
Orchardgrass	6.1a	4.3a	25a	60a	2,130a	1,246a	4.8a
Sm^2	1.1	0.7	5	12	1,400	819	0.9
Low wind	1.8 b	6.1a	21 b	50 b	2,130a	1,246a	4.0 b
High wind	5.8a	3.8a	48a	115a	2,860a	1,673a	6.9a
Sm^2	1.1	0.7	5	12	1,400	819	0.9
Low light			19 b	45 b	770 b	450 b	10.0 b
Medium light			33a	79a	2,180ab	1,275ab	6.2 b
High light			42a	101a	5,270a	3,083a	3.3 c
Sm^2			4	10	990	579	0.7

[1] Values in a column not having a letter in common are different at the 5% level of significance according to Duncan's multiple range test.

[2] Standard error of mean.

MATERIALS AND METHODS

The studies were conducted during the winter at Ithaca, N. Y., in a glasshouse in which air temperatures during the day were held near 25°C.

Cultivation of plant material. Three flats each of alfalfa (*Medicago sativa*) and orchardgrass (*Dactylis glomerata*) were established in 40 x 30 x 8 cm wooden boxes filled with vermiculite. The stands were broadcast on 2 December 1965 at approximately 40 kg ha^{-1}. Thereafter, they were arranged on benches and watered at intervals sufficient to keep the entire rooting zone moist with Hoagland's No. 2 solution. All plant material was sprayed at weekly intervals with an organo-phosphorus pesticide (Phosdrin). On 7 February 1966, all plant material which jutted above the bulk of the leaf canopy was clipped off. A narrow ruler was then inserted at 20 randomly selected places per flat, and the height of the uppermost foliage touching the ruler recorded. The mean height of plant material in the two most uniform flats of each species, which were used for subsequent wind tunnel measurements, was 8.1 cm for alfalfa and 14.0 cm for orchardgrass. The coefficients of variation of the stand height determinations (40 measurements) were 70% and 158% respectively for the alfalfa and orchardgrass. All stands were completely vegetative and were intercepting 85-90% of the radiation to which a selenium photocell is sensitive. Photosynthesis and transpiration data were collected between 8 and 15 February 1966, when the air temperature in the glasshouse was 22-25°C and the relative humidity of the air was 50-60%.

Determination of photosynthesis and transpiration. For this purpose, an open circulation wind tunnel (Fig. 1) with a 30 x 30 x 90 cm working section was used. Air flow was controlled by a centrifugal fan powered by a 90 volt D.C. General Electric 'thymotrol' motor located at the outlet. Air, drawn from the upper part of the glasshouse, was passed through a 90 x 90 x 10 cm screen of fibrous packing material, a 90 x 90 x 80 cm mixing chamber, and two 0.5 x 0.5 mm wire mesh screens before being throttled into the working section. The whole apparatus, which had been designed and constructed by Therm Inc.[3] allowed accurate control of flow, especially at low windspeeds.

Windspeed profiles were measured at the center of the trailing edge of the working chamber with a Hastings Raydist R-2 air meter equipped with an N-7 non-directional probe. Two windspeed control settings were selected to produce maximum windspeeds in the test section of:

Regime	Windspeed (cm sec^{-1})
Low	26
High	165

These speeds were chosen because little is known about the behavior of forage stands at low windspeeds. Furthermore, it was felt that the short wind tunnel in which the studies were undertaken was best fitted to work at low windspeeds.

The sides and top of the working section consisted of 0.5 cm clear lucite; the floor was completely filled with two of the plant-containing wooden flats placed end-to-end in a specially made holder, and sealed in with tape. On top of the working section rested a clear lucite tray with 10-cm sides which was filled with distilled water; immersed in this water were 12 Sylvania 300 watt incandescent reflector spot lamps, 15 cm on centers, surrounded by several copper cooling coils, and a small electric stirrer. A 5-cm layer of water was left below the lamps as an infrared filter. The working section, water bath, and lamp mountings were covered with a screen of aluminum foil. Overheating of the air within this housing was avoided by aspirating with a small fan.

Japanese EKO tube solarimeters used for sensing radiation within the working chamber were used without a filter for total short-wave radiation, and with a colored acetate-base filter for near-infrared radiation, as described by Allen and Brown (1). Twenty cm below the chamber ceiling, the values at the various radiation intensity regimes were:

Regime	Total short-wave (cal cm^{-2} min^{-1})	Visible (cal cm^{-2} min^{-1})
Low	0.2	0.05
Medium	0.6	0.18
High	1.9	0.70

These intensities were chosen to encompass a range similar to that experienced in the field. Nevertheless, the proportion of visible components in the total short-wave radiation, which increased from 25% to over 35% at the low and high intensities respectively, was less than is found in the field.

In operation, samples of air were withdrawn simultaneously from several different levels both above and below the top of the crop at the trailing edge of the flats. For this purpose, horizontally placed 2-mm copper intake tubes were connected via short lengths of tygon tubing to airtight electric aquarium pumps of 1 liter min^{-1} capacity. The water vapor content of the samples was determined by drawing the air from each level through two 7-cm long magnesium perchlorate absorption tubes which were carefully weighed before and after a "run." The discharge from each pump was passed into a volume-calibrated PVC beachball (about 24 liters) which acted as a fixed volume device. Speed of pumping was adjusted so that the balloons filled in 45-60 minutes. The carbon dioxide content of the dry air in each balloon was determined by using a Mine Safety Company differential infrared carbon dioxide analyzer, which was accurate to the nearest 0.00003 vol. %. Absolute CO_2 concentration of the intake air, determined by comparing samples with a standard, was generally about 0.04 vol. %.

The fluxes of water vapor and carbon dioxide were obtained by combining windspeed and concentration data. The fluxes from 3-cm deep horizontal layers, taken sequentially from the floor to the ceiling of the working section, were first calculated as:

$$\frac{\bar{u}\ (C - C_1)\ WD}{A}$$

where $\bar{u}$ is the mean windspeed of air leaving the working section at the height considered, C_1 is the concentration of either CO_2 or H_2O vapor (g m^{-3}) of the intake air (taken as the concentration of air leaving the chamber in the free stream), C is the mean concentration of either CO_2 or H_2O vapor of air leaving the working section at the height considered, W is the width of the working chamber, D is the depth of the layer considered, and A is the floor area covered by plant material. The total flux was obtained by adding the values for the number of layers:

$$\sum_{i=1}^{n} \frac{\bar{u}_i \, (C_i - C_1) \, WD}{A}$$

No air temperature data are reported, as it was found after the investigations that the fine wire thermocouple data were not free of radiation errors.

Analysis of data. The wind velocity profiles at low light intensity were analyzed by the graphical method (13) according to the "log profile law":

$$\bar{u}_{(z-d)} = \frac{u^*}{k} \cdot \ell n\left(\frac{z-d}{z_o}\right)$$

where $\bar{u}_{(z-d)}$ is the mean windspeed at height z-d above ground level, u* is the friction velocity, k is the von Karman constant, and z is the height measured from ground level. The parameter d (the effective displacement length) is the distance from the ground surface to the plane (the displaced reference plane) at which the momentum exchange coefficient extrapolates to zero, and z_o (the effective roughness length) is the distance from the displaced reference plane to the surface at which the wind profile extrapolates to zero velocity.

The homogeneity of the data was tested by analysis of variance and F-test procedures. The error term, which included all nonsignificant interactions, was obtained by testing each of the first-order interactions against an error term which included all other interactions. In the wind profile parameter analyses, three replicate 'runs' carried out at each of the two windspeeds for both alfalfa and orchardgrass were included. For the net photosynthesis, evapotranspiration, and efficiency of water use analyses, separate 'runs' undertaken at the low and high windspeed regimes under each of three radiation settings for both alfalfa and orchardgrass were used.

RESULTS AND DISCUSSION

The wind velocities immediately above the uppermost foliage of both stands were unaffected by radiation intensity. These velocities were approximately 21 and 55 cm sec^{-1} for respective free stream velocities of 26 and 165 cm sec^{-1}. Such values would be representative of the field on fairly calm days. The effective displacement length, d, was greatest ($P < 0.05$) at the low windspeed in both species, but was not significantly different between the orchardgrass and alfalfa. The effective roughness length, z_o, was greatest ($P < 0.05$) at high windspeed in both species, and also larger ($P < 0.05$) in orchardgrass (Table 1). Such findings contradict earlier work which has shown z_o to decrease with windspeed in stands of grass (4) and of alfalfa (16). In the latter investigations the windspeeds somewhat above the crop surface were all above approximately 2 m sec^{-1}, whilst in the present work they were all below 2 m sec^{-1}. Stands of orchardgrass and alfalfa probably show, therefore, both an increase and a decrease in z_o with windspeed depending upon the range considered. Such findings have been reported for rice by Tani (18) and wheat by Stoller and Lemon (16).

The profiles of carbon dioxide and water vapor concentrations varied considerably, depending on both radiation intensity and windspeed (Fig. 2). The maximum difference in carbon dioxide concentration between the free stream and air at the surface of the crop was approximately 0.003 vol. % at the highest radiation intensity and the lowest windspeed. A similar fall in concentration appears only rarely during the day in the field (17), probably because wind velocities are generally higher than at the low setting in the present work.

The carbon dioxide flux (net photosynthesis) determinations varied from 15 to 71 mg dm^{-2} hr^{-1} with alfalfa and from 9 to 39 mg dm^{-2} hr^{-1} with orchardgrass. These latter figures compare unfavorably with dry matter increment data obtained in the field. On the assumption that 44 g of carbon dioxide are required to produce 30 g of dry matter, the commonly attained dry matter increment of 10 g m^{-2} day^{-1} (9) equals an average net carbon dioxide assimilation of 63 mg dm^{-2} hr^{-1}.

The net photosynthesis at medium radiation was greater ($P < 0.01$) than under the lowest radiation regime, but not significantly different from that at the highest radiation setting (Table 1). This finding contrasts with results obtained by Thomas and Hill (19), who reported an increase in the net photosynthesis of field stands of alfalfa to midday radiation intensities, and by Hesketh (8), who recorded an increase in the net photosynthesis of individual leaves of orchardgrass to radiation values of at least 1.3 cal cm^{-2} min^{-1}. Such differences may have resulted because the material used in the present work was grown under relatively low light in a glasshouse in winter. Also, the present study was undertaken under artificial conditions with (a) illumination that contained more near infrared radiation than in the open, and (b) a 'sky' that was warm and as a consequence emitted more thermal radiation to the crop than is common in the field. The low light intensities incident during growth of the stands would have resulted in leaves with a lower maximum rate of net photosynthesis than those grown in the field (2). Also the high levels of near infrared and thermal radiation during the experimental periods may have resulted in stomatal closure through dehydration (3).

The water vapor flux (evapotranspiration) determinations varied from 665 to 9,000 mg dm^{-2} hr^{-1} with alfalfa, and from 360 to 4,390 mg dm^{-2} hr^{-1} with orchardgrass. The values at the medium radiation intensity were not significantly different from those at both the highest and lowest radiation intensities, but the flux at the highest intensity was significantly greater than that under the lowest regime (Table 1). This apparent increase in evapotranspiration to the highest radiation value contrasts with the pattern of change noted for net photosynthesis; a difference which may be explainable because the stands were grown at low light intensity. Such conditions would result in leaves with both a low maximum rate of net photosynthesis (2) and a thin cuticle (5). The low maximum rate of net photosynthesis would result in the observed pattern of behavior if no stomatal closure occurred at the high radiation intensities. Further, leaves with a thin cuticle lose large amounts of water when the stomata are closed (3), and so would behave in the manner observed even if stomatal closure had occurred at the high radiation values.

The ratio of evapotranspiration to total short-wave radiation, calculated on the assumption that the latent heat of evaporization was 585 cal g^{-1}, was greatest under the lowest radiation regime:

Radiation regime	Evapotranspiration/radiation
Low	0.42
Medium	0.36
High	0.27

This finding is not attributable to a difference in the spectral composition of the radiation at the contrasting intensities, because the proportion of visible components was greatest under the highest radiation regime. It contrasts with the approximately constant ratio through the day in field stands of alfalfa (19), and may have resulted from stomatal closure at the higher radiation loads. On the other hand, it may be directly attributable to the influx of thermal radiation from the warm 'sky.' Because of this latter component, the measured short-wave radiation values at low intensity would comprise a smaller fraction of the total radiation input than at the higher intensity.

The ratios of net photosynthesis (P_N) to evapotranspiration (E_t) were computed after converting the data to an energy basis. It was assumed that 2,400 calories are required to fix 1 g of carbon dioxide into plant material, and that 585 calories are used in evaporating 1 g of water. The computed ratios, which ranged from 0.3 x 10^{-2} with both alfalfa and orchardgrass at the highest radiation and the lowest wind, to 1.5×10^{-2} for alfalfa at the lowest radiation and the highest wind, encompass the figures ($0.4 - 0.6 \times 10^{-2}$) which can be calculated for alfalfa in the field from data presented by Thomas and Hill (19). The ratios decreased along with insolation (Table 1), as predicted from theory by de Wit (23).

The mean net photosynthesis was greater ($P < 0.05$) at the higher windspeed although there was a significant ($P < 0.01$) interaction between windspeed and radiation intensity. This stems from the independence of net photosynthesis and wind at low light. By contrast, the evapotranspiration did not differ significantly between the two windspeeds.

The water use efficiency (P_N/E_t) was greater at the high windspeed (Table 1), as found in the field with maize (14). Because both of these investigations were undertaken in a range of windspeeds in which z_o increased with wind, however, the results are not applicable under conditions in which z_o decreases with wind; this is unlikely to occur often in the open with maize (16), but frequently with grasses (4), rice (18), alfalfa and wheat (16). Furthermore, the results do not imply that P_N/E_t is favorably affected by an increase in windspeed at all times when z_o is directly linked to wind. This follows from a consideration of the mechanism through which windspeed exerts its effects. When z_o increases with wind, enhanced turbulence above the crop is reflected in more vigorous air movement within the canopy (16), and because an increase in the speed of air movement around individual leaves decreases the thickness of the leaf boundary layer in a reduction in the effective air resistance (r_a) to carbon dioxide, water vapor, and sensible heat transfer (6). In the absence of changes in stomatal aperture, such a reduction in r_a will affect photosynthesis and sensible heat flux directly. The increase in the latter component may result in a lowering of leaf temperature; a change which tends to offset the direct effects of a lower r_a on evapotranspiration. Under such conditions the balance of factors may lead to an increase in the efficiency of water use with increased wind, as occurred in the present work. Under other conditions, depending on the levels of radiation, air temperature, and humidity, the balance may be such as to increase evapotranspiration equally if not more than photosynthesis with wind. More detailed considerations of the various factors determining the distribution of energy between sensible heat flux and evapotranspiration have been given by Raschke (15), Gates (7), and Knoerr (11).

CONCLUSIONS

These investigations, by showing that it was possible to measure small wind-induced changes in the rate of net photosynthesis, suggest that further studies of photosynthesis and transpiration of forage stands could usefully be undertaken in a small wind tunnel of the type described here. They emphasize, however, that care should be taken to insure that both the short-and long-wave radiation environments are comparable to those in the open. In this connection, two points merit attention: (a) the cooling of the lamps should be such that the 'sky' temperature is less than that of the crop surface, and (b) the depth, and possibly also dye content, of water filter should be adjusted at each radiation setting to insure that the ratio of visible-to-near infrared radiation remains constant, preferably at the ratio commonly found in the field.

Nevertheless, it should be remembered that it is impossible to reproduce natural turbulence in a wind tunnel. For one thing, the mean eddy size is inevitably much smaller than in the open. Thus, the role of wind tunnels is rather as a complement to glasshouse, growth room, and plastic canopy studies, in order to allow control of one further component of the aerial environment, rather than as a replacement for studies in the field under completely natural conditions.

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FOOTNOTES

1. Contribution from the Northeast Branch of the Soil and Water Conservation Research Division, ARS-USDA, in cooperation with the New York State Agricultural Experiment Station at Cornell University, and the Atmospheric Sciences Research Division, U. S. Army Electronics Command, Fort Huachuca, Arizona. Department of Agronomy Series Paper No. 717. Trade names and company names are included for the benefit of the reader and do not infer any endorsement or preferential treatment of the product listed by the U. S. Department of Agriculture.
2. Research Associates, Department of Agronomy, Cornell University, and Research Soil Scientist, SWC, Agricultural Research Service, USDA and Professor in Agronomy, Cornell University, Ithaca, N. Y.
3. Therm-Electric Meters Co., Inc., Ithaca, N. Y. Project No. JO 015-0004.

Table 1. Wind profile parameters, net photosynthesis, and evapotranspiration for alfalfa and orchardgrass stands in a wind tunnel.

Crop	Roughness length (z_o) cm	Displacement length $(d)^1$ cm	Net photosynthesis $(P_N)^1$ $mg\ dm^{-2}\ hr^{-1}$	Evapotranspiration $(E_t)^1$ $mg\ dm^{-2}\ hr^{-1}$	Efficiency of water use $(P_N/E_t)^1$ 10^{-2}
Alfalfa	1.5 b	5.6 a	45 a	3,330 a	0.8 a
Orchardgrass	6.1 a	4.3 a	35 a	2,130 a	0.6 a
Sm^2	1.1	0.7	5	1,400	0.1
Low wind	1.8 b	6.1 a	21 b	2,130 a	0.4 b
High wind	5.8 a	3.8 b	48 a	2,860 a	0.7 a
Sm^2	1.1	0.7	5	1,400	0.1
Low light			20 b	770 b	1.1 a
Medium light			41 a	2,180 a b	0.8 b
High light			42 a	5,270 a	0.3 c
Sm^2			4	990	0.1

---

[1] Values in a column not having a letter in common are different at the 5% level of significance according to Duncan's multiple range test.

[2] Standard error of mean.

FIGURE LEGENDS

Fig. 1. Wind tunnel used for the present work.

Fig. 2. Profiles of the carbon dioxide and water vapor content of air above the alfalfa and orchardgrass stands. Data expressed as a function of height above ground for two windspeeds and three radiation (H, M, L) regimes. Open and solid symbols represent low and high windspeeds, respectively.

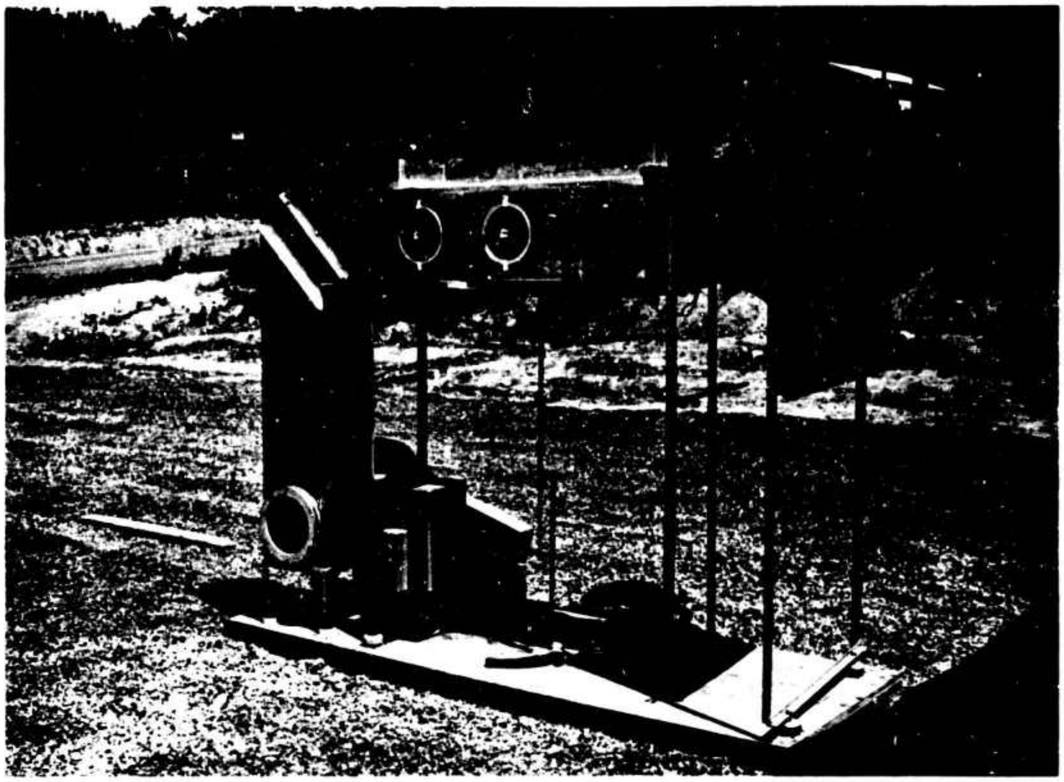

Figure 1

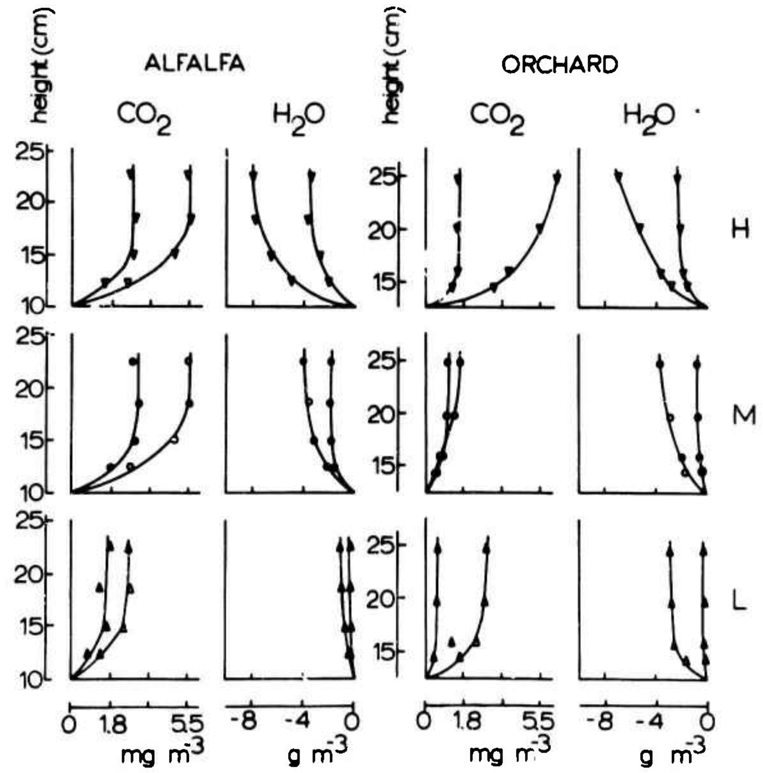

Figure 2

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Fort Huachuca, Arizona

13. ABSTRACT

Vegetative stands of alfalfa and orchardgrass, grown in flats in a glasshouse, were investigated in a small wind tunnel. The windspeed parameters of the crop surfaces were determined at low radiation intensity at each of two windspeeds; and the rates of net photosynthesis and evapotranspiration were measured at the two windspeeds at each of three radiation intensities.

The roughness length (z_0) increased with windspeed and was greater in orchardgrass. Rate of net photosynthesis, but not evapotranspiration, also increased with windspeed. In consequence, water-use was most efficient under the highest wind regime. The rate of net photosynthesis increased to the intermediate radiation intensity, whereas evapotranspiration increased and water-use efficiency decreased to the highest radiation regime.

The work indicated that a small wind tunnel of the type described would be useful for further studies of the photosynthesis and transpiration of forage stands.

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Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Plant studies in wind tunnel Radiation Windspeed Net photosynthesis Evapotranspiration						

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