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The Macroclimate and Microclimate of Coastal Foredune Grasslands in Cape Hatteras National Seashore

by

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ABSTRACT — At Bodie Island , hourly air and soil temperatures at two depths on the front of a foredune were recorded in 1971. In 1972 hourly soil temperatures at three depths (20, 40, and 60 cm) on the front, top, and back of the foredune, plus air temperatures at the top of the dune were recorded at the same site. Data were also collected approximately monthly during 1971 and 1972 on soil moisture at 20, 40, and 60 cm, sand movement and soil cation levels (K, Na, Ca, and Mg) at the surface and at 20, 40, and 60 cm on the front, top, and back of the foredune. The Bodie Island Ranger Station (about 100 m away) collected daily maximum and minimum air temperatures, rainfall data, and data on wind speed and direction.

INTRODUCTION

There is remarkably little basic information about the microclimate of sand dunes (Chapman, 1964; Ranwell, 1972). For the most part, what little bit of information is available has been collected in Europe, primarily in England. In North America, and in North Carolina in particular, there are only a handful a papers that include any microclimatic data on coastal dunes. Au (1969, 1974) gives average weekly air temperatures, average weekly vapour pressure deficits, and weekly accumulated wind runs from the top of a rear dune on Shackleford Bank, North Carolina. His paper also contains some soil moisture determinations, soil nutrient measurements and annual sand movement data from the foredune on Shackleford. A few summer spot measurements of foredune soil temperatures, soil moistures, soil salinity and salt spray inputs from Bogue Bank, North Carolina are found in Oosting and Billings (1942). The remaining published works deal with soil nutrients (Berenyi, 1966; Woodhouse and Hanes, 1966), sand movement (Savage and Woodhouse, 1968) and salt spray (Boyce, 1954).

Because of the paucity of coastal dune microclimatic data, I carried out a study on coastal foredunes in 1971 and 1972 at Bodie Island in Cape Hatteras National Seashore, North Carolina, the primary purposes was to gather microclimatic data and evaluate their ecological significance. As part of this study, data was collected on soil cation levels (K, Na, Ca, Mg), soil moisture, soil temperatures, sand movement, and salt spray inputs on the front (oceanside), top, and back of the foredune. Data was also collected

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on air temperatures and rainfall. An experimental evaluation of these microclimatic variables on the floristic composition of foredune grasslands has already been published (van der Valk, 1974a) and also a nutrient budget study to evaluate the significance of salt spray cation inputs (van der Valk, 1974b). In this paper, I will present the microclimatic data collected at Bodie Island and compare certain features of the foredune microclimate to the macroclimate of the Cape Hatteras area.

SITE DESCRIPTION

The Bodie Island site (Lat. 35° 50′N; Long 75° 33′W) is located at the northern end of Cape Hatteras National Seashore, North Carolina adjacent to the Bodie Island Ranger Station. The Ranger Station is a U. S. Weather Bureau Station collecting data on air temperature, rainfall, wind speed and direction. The macroclimate of the area is Cfa in the Köppen system.

The foredune was constructed using sand fences in 1962 and was approximately 5.7 m tall during the study. The vegetation on the front and top of the foredune was a sparse mixture of three grasses *Ammophila breviligulata* Fern., *Uniola paniculata* L., and *Panicum amarum* Ell. On the back of the dune, *Ammophila breviligulata* and *Uniola paniculata* were the dominant grasses, but several forbs were as or more abundant, *viz, Erigeron canadensis* L., *Gnaphalium obtusifolium* L. and *Solidago sempervirens* L. Altogether 20 species of forbs were present on the back (van der Valk, 1973; 1975).

METHODS

Salt spray was measured using salt spray traps and estimated from bulk precipitation as outlined in van der Valk (1973, 1974b).

Soil nutrient samples were collected on the front, top, and back of the foredune at the surface and at 20, 40 and 60 cm. Samples were collected weekly during the summer of 1971 and at approximately monthly intervals during the remainder of the study. Cations (K, Na, Ca, Mg) were eluted from 50 gm subsamples of each soil sample with 50 ml of deionized water and the cation concentrations in the extract were determined using standard atomic absorption techniques (van der Valk, 1974b). Soil moisture samples were collected at the same places and depths and at the same time as soil nutrient samples, except no surface samples were collected. Soil moisture was determined gravimetrically (van der Valk, 1973) with the samples oven dried at 80° C.

Soil and air temperatures on the front of the foredune in 1971 were recorded continuously on a three channel mechanical thermograph. The air temperature sensor was housed in a standard U. S. Weather Bureau instrument shelter. Soil temperature sensors were buried horizontally at approximately 10 and 20 cm. In 1972 an Atkins single channel 10-point thermistor temperature recording system was installed. Air temperatures were measured about 35 cm above the sand surface in a small white shelter open on the bottom and toward the north. Soil sensors were buried horizontally at 20, 40, and 60 cm on the front, top, and back of the dune. Each of the 10 sensor was monitored in sequence once an hour for 5 minutes. Average temperature calculations for both years are based on 24 hourly readings per day.

Sand movements was measured using a grid of fence posts 10 m apart along the length of the dune and 5 m apart across the dune. There were 88 posts altogether. In July 1971 each post was exactly 1 m in height and during 1972, the height of each post was measured at approximately monthly intervals. Relative sand level changes were calculated for each zone by averaging the readings from all fence posts in a zone. There were 33, 22 and 33 posts on the front, top and back respectively.

Table 1. Soil cation (K, Na, Ca, Mg) levels (kg/ha) at the surface and at 20, 40 and 60 cm below the surface on the front, top and back of the foredune at Bodie Island.

	K			Na			Ca			Mg		
	Front	Top	Back	Front	Top	Back	Front	Top	Back	Front	Top	Back
SURFACE												
Mean	2.7	2.4	1.9	39.0	17.6	16.0	7.0	7.0	5.6	7.2	4.2	4.0
± SD	2.3	1.9	1.1	55.6	20.3	17.2	5.6	10.4	3.0	8.0	2.8	2.7
Min	0.29	0.11	0.0	2.2	0.74	1.2	2.3	0.22	2.8	2.2	0.26	1.8
Max	8.7	5.6	4.9	164.6	61.4	66.8	21.4	48.9	14.0	27.3	9.6	12.3
20 cm												
Mean	2.0	2.2	1.7	10.9	10.0	5.0	4.7	4.5	4.5	2.5	2.4	2.0
± SD	1.1	1.5	0.65	13.4	18.4	5.2	2.1	2.0	1.8	1.6	1.9	1.0
Min	0.59	0.80	0.27	0.64	0.72	0.88	2.1	1.9	2.0	0.92	1.1	0.93
Max	5.3	6.2	3.1	57.0	72.4	23.2	10.4	11.4	10.2	7.7	10.3	5.3
40 cm												
Mean	2.1	2.2	1.8	9.0	12.4	9.8	5.0	4.9	5.6	2.5	2.8	2.1
± SD	0.72	1.0	1.2	13.3	24.1	23.4	3.6	2.5	2.4	1.5	2.8	2.3
Min	0.66	0.62	0.86	1.1	0.60	0.57	1.8	2.2	2.9	0.83	1.2	0.65
Max	3.8	5.7	7.5	71.9	113.3	123.7	20.3	13.6	14.4	8.0	13.6	13.2
60 cm												
Mean	1.9	1.9	1.6	10.9	5.5	5.6	5.3	4.7	5.7	2.2	2.1	1.9
± SD	0.69	0.76	0.83	15.9	4.0	8.6	2.9	1.9	2.3	1.3	0.81	1.4
Min	0.63	0.34	0.22	1.2	0.83	0.65	2.4	1.6	1.8	1.0	1.0	0.41
Max	3.7	3.6	4.5	69.2	16.0	45.3	17.0	9.7	12.8	7.8	3.9	8.0

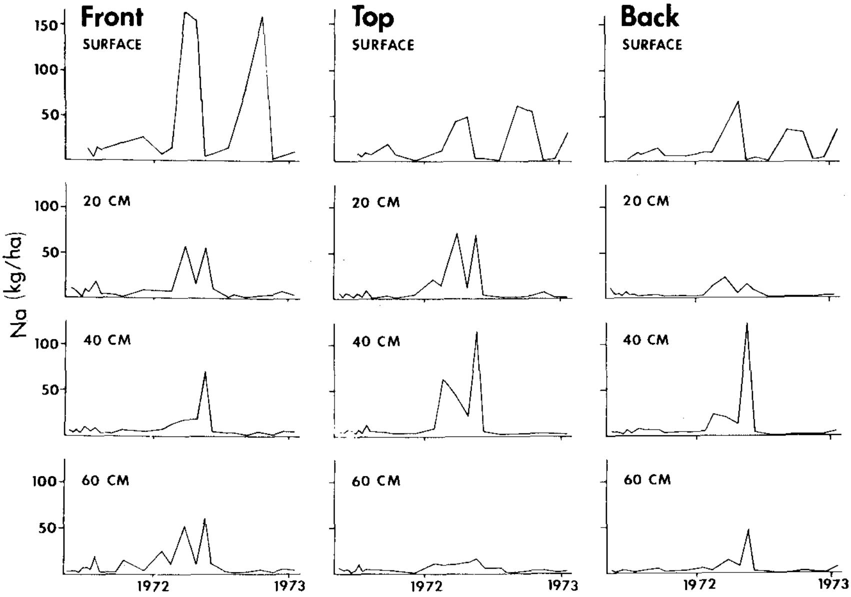

Fig. 1. Sodium levels (kg/ha) on the surface and 20, 40 and 60 cm below the surface on the front, top, and back of the foredune at Bodie Island. Surface samples were collected from 1 June 1971 to 18 January 1973 and subsurface samples were collected from 15 May 1971 to 18 January 1973.

RESULTS AND DISCUSSION

Annual salt inputs vary tremendously from zone to zone on the foredune. On the front 77, 1300, 80, and 110 kg/ha of K, Na, Ca and Mg are deposited while on the top and back these same four cations have annual inputs of 42, 740, 44 and 100 kg/ha and 18, 310, 19 and 42 kg/ha. Of the total annual input of salt spray (defined as the sum of all four cations), 56% falls on the front of the foredune, 31% on the top and 13% on the back (van der Valk, 1973; 1974b). Oosting and Billings (1942) found similar percentages in summer salt spray deposition on foredunes. A study of cation inputs by Art et al. (1974) on the back of a rear dune on Fire Island, New York also found that salt spray is a major source of cations for coastal ecosystems.

The depositional pattern of these annual inputs of salt spray is seasonal in nature. The bulk of the salt spray in any year at Bodie Island is deposited during storms in the spring, winter, or fall. As a result of this uneven distribution of inputs, soil cation levels fluctuate tremendously during the year (Fig. 1, Table 1). The minimum and maximum level of all four cations measured differ by at least one order of magnitude at any level in the soil (Table 1) and can vary by as much as four orders of magnitude, e.g. on the top at 40 cm, Na levels range from 0.60 to 113.3 kg/ha. The maximum subsurface levels of K, Na, Ca and Mg found were 7.5, 124, 20 and 14 kg/ha. The minimum subsurface levels of the same four cations were 0.22, 0.57, 1.6 and 0.41 kg/ha (Table 1).

Figure 1 also gives a rough indication of the residence or turnover time of Na in the upper sand layers of the foredune. The other three cations show the same general pattern. Na deposited on the dune surface in March 1972 appears at subsurface levels in April and is gone from the upper 60 cm by May. The high level of Na on the surface from March to May is a result of two periods of deposition which were not distinguishable in the surface samples, but which are quite distinct in the subsurface layers. The second deposition occured in April, appears on the subsurface layers in May and is gone by June. In October 1972, large amounts of salt spray were again deposited on the surface, but these deposits are never detected at lower levels (Fig. 1). This salt spray had leached through the upper 60 cm of soil before the next samples were taken in December. It appears that the residence time of Na in the upper layers of the dune is in the order of 30 days or less. This agrees with calculations of surface Na turnover times previously made using salt spray input data (van der Valk, 1973), which indicated average turnover times of 9 days on top and 11 and 20 days on the front and back respectively. Boyce (1954) was the first to demonstrate that rainfall is responsible for this rapid leaching of salt spray through dune soils and that, as a result, coastal dune soils are very low in nutrients. Multiple regression analysis of the data collected showed that soil surface Na levels on the front of the dune can be predicted using the total wind run from the NE, the Na concentration in the bulk precipitation (i.e., salt spray) and rainfall data ($r^2 = 0.71$).

Although foredune plants appear to be completely dependent on salt spray and rainfall for their K as indicated by the very low minimum values of this cation in subsurface layers (Table 1), Ca and Mg are also being supplied to the soil by the breakdown of sea shell fragments. This is reflected in the higher minimum levels of Ca and Mg in most subsurface soil layers compared to Na (Table 1). Measurements of acid extracted calcium and magnesium in Cape Hatteras foredune soils indicate that 5,100 to 8,200 kg/ha of Ca and 46 to 54 kg/ha of Mg are present (van der Valk, 1975; see also Berenyi, 1966).

Total annual precipitation, generally all in the form of rain, in the northern portion of Cape Hatteras National Seashore is in the neighborhood of 1,400 to 1,500 mm/year. At Bodie Island in 1971 and 1972 the total precipitation was 1,640 and 1,606 mm respectively. This precipitation is fairly evenly distributed during the year varying generally from 90 to 150 mm/month. The wettest months are normally July, August, and September. During the study period actual monthly precipitation varied from 36 to 381 mm.

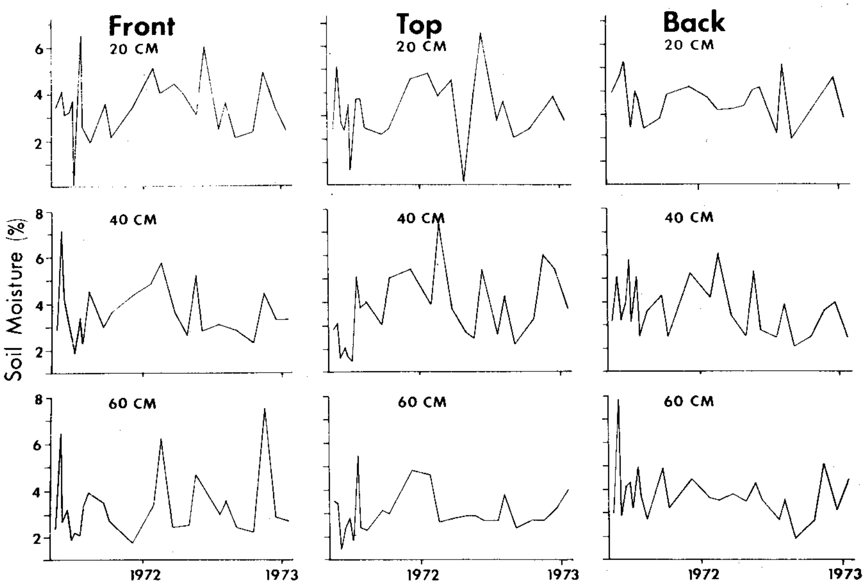

Fig. 2. Soil moisture (%) on the front, top, and back of the foredune at 20, 40 and 60 cm. Data was collected from 15 May 1971 to 18 January 1973.

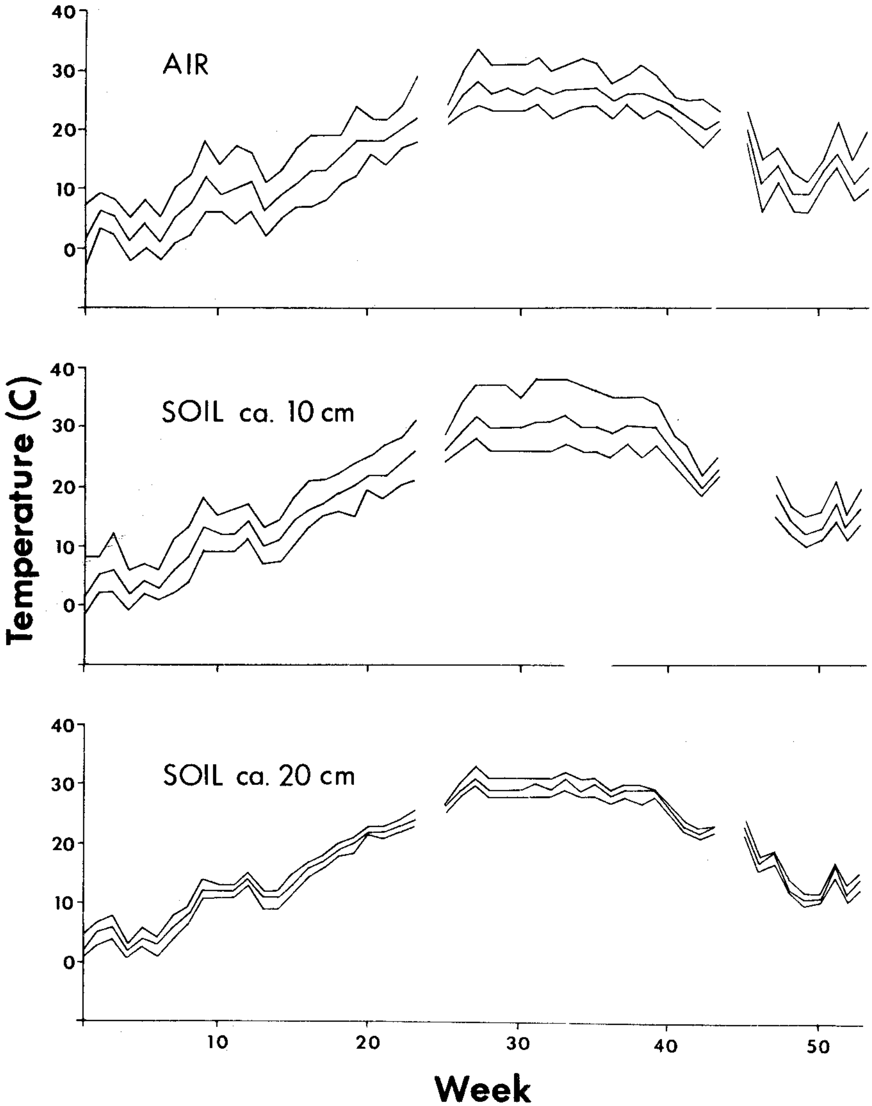

Fig. 3. Weekly average maximum, minimum and daily air and soil temperatures on the front of the foredune during 1971. Gaps represent periods when data were not collected.

Because rainfall is adequate throughout the year, subsurface soil moisture levels (Fig. 2) are rarely low enough to be of any consequence biologically. Only on three occasions during the summer did subsurface soil moisture fall below 1%. This occured twice on the top and once on the front at 20 cm (Fig. 2.). Soil moisture for the whole foredune ranged from 0 to 6.8% at 20 cm, 1.5 to 7.3% at 40 cm and 1.5 to 7.8% at 60 cm. On the average soil moisture levels are slightly lower in summer than in winter, but they can vary greatly in either season. There is no significant difference in soil moisture among the three zones or among the three depths in any zone (van der Valk, 1974a).

During the study, the average soil moisture at Bodie Island was around 3.5%. Similar foredune soil moisture values to those in Fig. 2 are found in Oosting and Billings (1942) who found a range of 2.4 to 5.4% and Au (1969, 1974) 2 to 4% on foredunes. Au's data also show that rainwater moves down the foredune soil profile to 60 cm in a couple of days or less.

Figure 3 gives average weekly and average weekly maximum and minimum air and soil temperatures for the front of the foredune in 1971. The highest air temperature recorded was 39°C and the lowest —9°C. In 1971 the highest air temperature recorded at the Bodie Island Weather Bureau Station was 35°C and the lowest —9°C. At a depth of 10 cm, the highest and lowest soil temperatures were 43°C and —4° and at 20 cm were 34°C and 2°C. Weekly mean soil temperatures at 10 cm are usually higher than air temperatures by 1 to 5°C except occasionally during the winter. At 20 cm weekly mean soil temperatures are always equal to or lower than those at 10 cm. The weekly mean daily range of temperature is about 4 to 10°C for air temperatures, 5 to 11°C and 2 to 3°C for soil temperatures at 10 and 20 cm respectively. The only comparable data

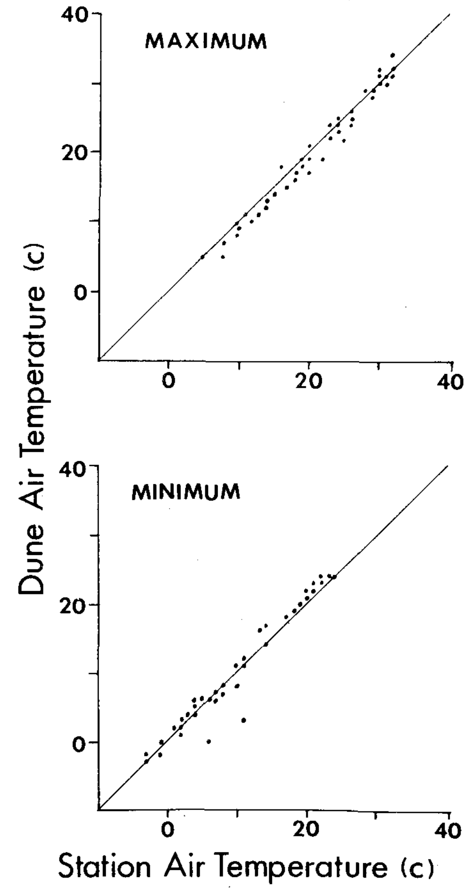

Fig. 4. Weekly average maximum and minimum air temperatures from the foredune plotted against weekly average maximum and minimum air temperatures at the Bodie Island Ranger Station during 1971. To facilitate comparisons, identical air temperatures at both sites are represented by the straight line in each graph.

Table 2. Selected air and soil temperatures (° C) from the front (F), top (T), and back (B) of the foredune at Bodie Island.

	Air temp °C	Soil Temperature 20 cm			40 cm			60 cm		
		F	T	B	F	T	B	F	T	B
					24 February 1972					
Minimum	6	7	7	8	6	7	8	7	7	9
Maximum	17	11	13	14	9	11	11	8	9	9
Mean	10	9	10	10	8	9	9	7	8	9
					2 March 1972					
Minimum	13	12	13	13	12	13	13	10	11	12
Maximum	25	16	20	19	13	15	15	11	13	13
Mean	17	13	16	15	13	13	13	11	12	13
					15 April 1972					
Minimum	11	15	14	14	14	14	15	13	14	15
Maximum	26	18	20	19	16	17	17	14	15	15
Mean	17	16	17	17	15	16	16	13	15	15
					4 August 1972					
Minimum	25	28	29	28	29	30	29	28	30	28
Maximum	42	33	36	35	32	33	31	30	31	29
Mean	31	31	32	30	30	31	30	29	30	28
					8 October 1972					
Minimum	10	17	15	17	19	18	20	21	20	21
Maximum	25	20	21	20	20	20	21	22	22	22
Mean	17	19	18	20	20	19	20	21	21	22
					19 December 1972					
Minimum	-2	3	1	3	4	5	6	8	7	9
Maximum	14	6	6	7	5	6	7	9	8	10
Mean	4	4	4	5	5	5	7	9	8	10

for North Carolina dunes is found in Au (1969, 1974). He recorded air temperatures for a year on the top of a rear dune on Shackleford Banks, North Carolina and found that air temperatures ranged from 39 to —5° C. His results are very similar to those found in this study. A few measurements made by Oosting and Billings (1942) of summer soil temperatures are comparable to those in Fig. 3.

A comparison of mean weekly maximum and minimum air temperatures in 1971 between the foredune and the Bodie Island Weather Bureau Station is found in Fig. 4. Mean weekly maximum air temperatures are higher on the foredune by 1 or 2° C during the hottest weeks of the summer, but are usually slightly lower the rest of the year. Mean weekly minimum air temperatures are, on the other hand, almost always a degree or so higher on the foredune, except during the coldest weeks of winter. There is an excellent correlation between dune and station air temperatures (Fig. 3). This striking similarity of mean weekly air temperatures is undoubtedly due primarily to the close proximity of the two sites. They were only about 100 m apart.

The 1972 temperature data are unfortunately very piecemeal because of repeated malfunctions and breakdowns of the Atkins equipment. However, enough data was collected over the year to make some generalizations about soil temperatures on the front, top, and back of the foredune. Table 2 contains some typical daily air and soil temperatures collected in 1972. Mean soil temperatures on the back and top of the foredune are usually higher by 1 or 2°C than on the front. This is a result of the NNW orientation of the foredune which means longer hours of direct sunlight on the back than front. These temperature differences are probably insignificant biologically; even the maximum soil temperature differences among zones is only 3°C (Table 2).

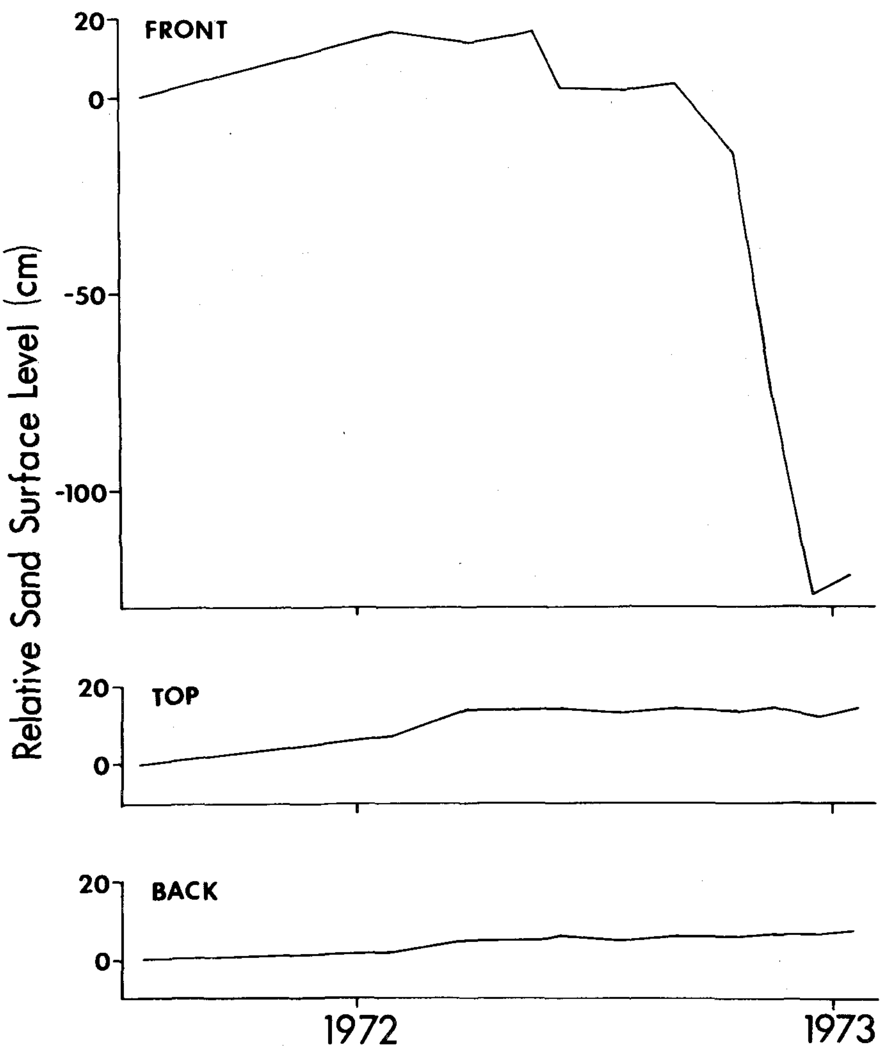

Fig. 5. Relative sand surface level changes on the front, top, and back of the foredune from July 1971 to January 1973.

Figure 5 summarizes the relative sand surface level changes at Bodie Island during 1972. On the back and top of the foredune, the mean sand level increased by 8 and 14 cm during 1972. Most of this sand accumulation was the result of a storm in February and little shifting of sand occured in these zones subsequently (Fig. 5). Sand surface levels on the front of the foredune underwent very substantial changes in 1972. Initially the mean sand level increased 17 cm from July 1971 to January 1972. The sand level then remained fairly constant until June when it begins to drop. By December 144 cm of sand on the front of the foredune had been lost because of wind and wave action. Au (1969, 1974) found annual sand level changes on the foredune at Shackleford to range from 4 to 8 cm. The loss of sand on the front reported here was caused primarily by wave action eroding away the front of the foredune. At the end of the study, the first row of fence posts had been washed out to sea. The general pattern of sand deposition on established foredunes in the Cape Hatteras area is accumulations of sand primarily on the front and top of the dune (Savage and Woodhouse, 1968; van der Valk, 1974a).

Of the environmental variables measured on the front, top, and back of the foredune, three do not vary significantly from zone to zone and appear to have little, if any, impact on the composition or functioning of foredune zonal ecosystems: soil moisture (Fig. 2), soil temperatures (Table 2) and subsurface soil nutrients (Fig. 1). The two variables that do differ significantly from zone to zone are salt spray and sand movement (Fig. 5) both of which are functions of wind speed and direction. Of the two sand movement has the most impact on the floristic composition of foredune communities on the front, top, and back. It buries or carries off seedlings or seeds of dune forbs during the winter months and prevents them from becoming established on the front of the foredune (van der Valk, 1974a). Salt spray is significant in understanding the functioning of foredune ecosystems, because it is the major source of nutrients. Plant growth on the foredune would be greatly reduced or eradicated if salt spray depostion were prevented (van der Valk, 1974b).

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