Soil Temperatures During Forest Fires and Their Effect on the Survival of Vegetation

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SOIL TEMPERATURES DURING FOREST FIRES AND THEIR EFFECT ON THE SURVIVAL OF VEGETATION

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(*With Plate* 12 *and six Figures in the Text*)

I. Introduction

Although some attention has been directed to soil temperatures in deserts (Buxton, 1924), the temperature of the soil during forest fires has received little consideration. The only work on this subject is that of Heyward (1938), who measured the temperature of the soil during the burning of grassland. The occurrence of a fire and the resulting high soil temperatures are important with regard to the death or survival of seeds or other plant organs, while the artificial burning of cultivated grassland, such as stubble, increases the soil temperature and may cause the death of micro-organisms.

In the following account, a practicable and simple method for measuring soil temperature is described, and data are given showing the temperatures at various depths below the surface in wet and dry soils. The survival of the vegetation is discussed with special reference to lignotubers (Kerr, 1925) and to the resistance of seeds to high temperatures.

II. Soil temperature

A. *Method*

The method employed for measuring soil temperature was as follows: At various depths in the soil, small glass tubes containing organic compounds of known melting-points were buried. The tubes were cut from thin-walled glass tubing of approximately $\frac{1}{8}$ in. internal diameter. Each tube was about 2 in. long and was sealed at one end. A small quantity of the crystalline organic compound was introduced, and into the open end of the tube was inserted a small roll of paper. The organic compounds used were:

Compound	M.P. (° C.)	Compound	M.P. (° C.)
Menthol	43	Pyrogallol	132
Thymol	50	Phenacetin	135
p-Anisidine	57	Benzoin	137
β-Brom-naphthalene	59	*m*-Nitrobenzoic acid	140
Coumarin	67	Benzilic acid	150
2:4-Dinitrotoluene	70	Salicylic acid	156
Vanillin	81	*p*-Amino-acetanilide	162
m-Dinitrobenzene	90	Camphor	175
α-Naphthol	95	Succinic acid	180
o-Toluic acid	105	*m*-Hydroxybenzoic acid	200
m-Toluic acid	109	Anthracene	213
β-Naphthylamine	111	Phthalimide	233
p-Nitrophenol	114	Anthraquinone	250
Benzoic acid	122		(sublimes)

The prepared tubes were placed in flat tins ($3\frac{1}{2} \times 2 \times \frac{3}{4}$ in.) which were buried in the soil.

In order to maintain, as far as possible, natural soil conditions, a deep hole was dug and small holes were scooped horizontally at various depths. The tins, containing the tubes, were filled with soil and inserted into the smaller holes horizontally so that the column of soil above the tubes was untouched. Temperatures below 43° C. were recorded by means of mercury thermometers pushed horizontally into the soil below the batteries of tubes. The cavities around the tins were packed tightly with soil and the soil from the large hole was replaced in approximately the same position from which it was removed. Fires were then lit on top, the diameter of each fire being about 2 ft., with the centre as near as possible above the tubes. After the fires had burned out, the tubes were recovered. The soil temperatures at the various depths were recorded by the melting of some of the organic compounds.

This method, though not as accurate as measurement with thermocouples (Heyward, 1938), has one advantage, namely, that the organic compounds will not melt after a momentary exposure, but require a temperature at or above the melting-point for some little time. Therefore their behaviour supplies more reliable information as to the effect of fire on plants.

B. *Results*

(*a*) *Soil temperatures during natural fires.*

Although fires are frequent in the *Eucalyptus* forests of Australia, trees are rarely burned out, and most of the fuel is supplied by the undergrowth. Consequently a fire was lit in a forest area which was known not to have been burned during the last six years. No extra fuel was added. The fire was allowed to burn out naturally; this required $\frac{3}{4}$ hr.

The soil temperature at a depth of 1 in. and that at the surface are given in Table 1. The surface temperature was obtained by pressing "melting-point tubes" horizontally into the soil so that the upper surface of the glass was just exposed.

Since fires in this district cross an area rapidly and do not burn for any length of time in the same place, these figures represent the probable temperatures during fire on the Hawkesbury Sandstone in the Sydney district.[1]

The temperatures recorded, though high at the surface, are surprisingly low at a depth of 1 in. The wide variation between the individual readings can be attributed to the varying amounts of dead plant material lying on the surface.

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[1] The Hawkesbury Sandstone formation has a wide exposure in the central coastal district of New South Wales. It is Triassic in origin and "consists mainly of massive sandstones and grits, which attain a maximum thickness of 1100 ft. at Sydney" (Süssmilch, 1914).

(*b*) *Probable maximal temperatures during fire.*

In order to estimate the probable maximal temperatures during fire, the equivalent (as dead fuel) of the vegetation (excluding trees) from a quadrat of 9 sq. ft. was built into a pile (diameter about 2 ft.) and lit. The fire burned for 2 hr. Such a fire will represent the probable maximal intensity, assuming that the whole of the vegetation is burned.

Batteries of tubes were buried at depths of 1 and 3 in. and thermometers

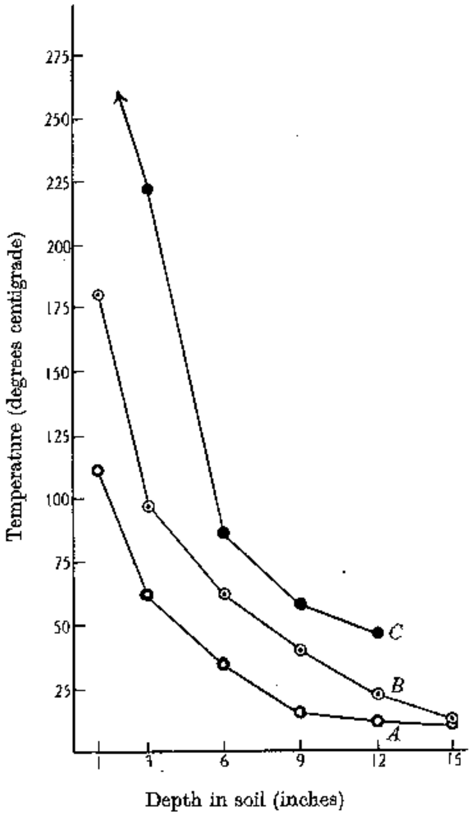

Fig. 1. Soil temperature during fire plotted against depth in the soil. *A*, probable maximal temperatures during fire (trees not burned); *B*, mean maximal temperatures if trees are burned, fire burning for 2 hr.; *C*, temperatures in extreme case, fire burning for 8 hr.

Table 1. *Temperatures at the surface and at a depth of* 1 *in. during a forest fire under natural conditions*

Depth	Temperature (° C.)					
Sample ...	1	2	3	4	5	6
Surface	111–114	175–180	200–213	135–140	81–90	132–135
1 in.	<43	57– 59	59– 67	43– 50	<43	43– 50

at 6, 9 and 12 in. below the fire. The results obtained are shown in Table 2 and are summarized graphically in curve *A*, Fig. 1. The surface temperature exceeded 250° C. At a depth of 1 in. the temperature was 114–122° C., while at 3 in. a temperature of 50–59° C. was recorded. Below this level, the temperature was not sufficiently high for a long enough period to harm any plant organ.

Table 2. *Probable maximal soil temperature at various depths below the surface. "T" after a temperature indicates that this temperature was measured with a thermometer*

Depth (in.)	Temp. (° C.)
Surface	>250
1	111–114
3	59–67
6	35 T
9	15 T
12	12 T
15	11 T

(c) *Maximal temperatures if trees are burned.*

To ascertain the highest temperature that could occur if the whole of the vegetation, including trees, were completely burned, the following method for estimating the amount of fuel was adopted: the number of trees in 100 sq. yd. was counted and the amount of fuel contained in them was roughly estimated. One-hundredth part of this amount of dry timber was collected and piled into a heap of 2 ft. diameter, together with fuel to account for the undergrowth, on a piece of land in which were buried batteries of tubes.

The temperatures obtained under these conditions are given in Table 3, column 2 and are represented graphically in Fig. 1, curve *B*. The temperature at a depth of 1 in. was 175–180° C., while at 9 in. the temperature exceeded 40° C.

Table 3. *Maximal soil temperature*

	Temp. (° C.)	
Depth (in.)	Fire burning for 2 hr.	Fire burning for 8 hr.
1	175–180	>250
3	95–105	213–233
6	59– 67	81– 90
9	40 T	57– 59
12	22 T	43– 50
15	13 T	—

The results obtained from this fire represent the mean maximal temperatures in a forest, i.e. if the whole of the fuel during the fire were distributed equally over the area.

Quite frequently, however, fallen trees or large stumps may burn for hours or even days. Therefore to gain some idea of the maximal temperature in such an extreme case, a fire, burning fuel at approximately the same rate as the one described above, was stoked for 8 hr. The results are given in Table 3, column 3, and Fig. 1, curve *C*.

These figures show that with long periods of time, the soil is appreciably heated to a depth of 1 ft., while at a depth of 1 in. the temperature exceeded 250° C. Thus the surface temperature, by extrapolation, would lie in the vicinity of 450° C.

The curves plotted in Fig. 1 were obtained from fires lit within 8 ft. of each other on a piece of land which showed fairly uniform water content and texture.

(*d*) *The effect of water content on soil temperature.*

Since the specific heat of sand is as low as 0·2, it is obvious that the specific heat of soil will depend largely on the water content. To illustrate this point, two fires were lit, one on a wet and the other on a dry soil. The water content of the soil before the fire is shown in Fig. 2, curves *A* and *B* respectively. The amount of fuel used for each fire was 20 lb. of *Eucalyptus* wood, cut from the same tree and piled on to an area of approximately 4 sq. ft. The fires were allowed to burn to embers, the time in both cases being $1\frac{1}{2}$ hr.

The results are shown in Table 4 and Fig. 3. From these data it can be seen that the water content of the soil influences the temperature during fire, a high water content causing a retardation in the conduction of heat.

Table 4. *Soil temperature in wet and dry soils*

	Temp. (° C.)	
Depth (in.)	"Wet" soil	"Dry" soil
1	132–135	>250
2	95–105	109–111
4	57– 59	90– 95
6	34 T	57– 59
8	26 T	43– 50
10	22 T	29 T
12	20 T	20 T

It is noteworthy that the water lost by evaporation diffuses into the atmosphere and does not pass downwards and condense, since the percentage of water in the soil at lower levels does not increase after fire (Fig. 2, curves *C* and *D*).

(*e*) *The effect of high temperatures on the physical properties of the soil.*

It is usually considered that the effect of fire is to reduce the amount of organic matter in the soil and thereby reduce the water-retaining capacity. The Hawkesbury Sandstone soils, having as a rule a low percentage loss on ignition, are not affected to any great extent by fire. Table 5 gives the physical properties of some soils before and after fire. From these figures it can be seen that fire does not appreciably alter the water-retaining capacity, loss on ignition or *p*H value.

Variations in sampling were avoided in the following manner: small fires were lit and soil samples were collected before and immediately after the fire, the second sample being collected beside the hole left after the first sample was removed. No plant ash or charcoal was included. The amount of fuel used in each fire was the same as that described in § (*b*).

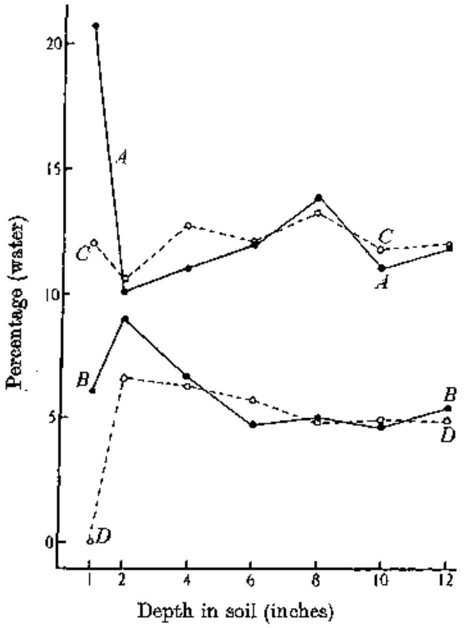

Fig. 2.

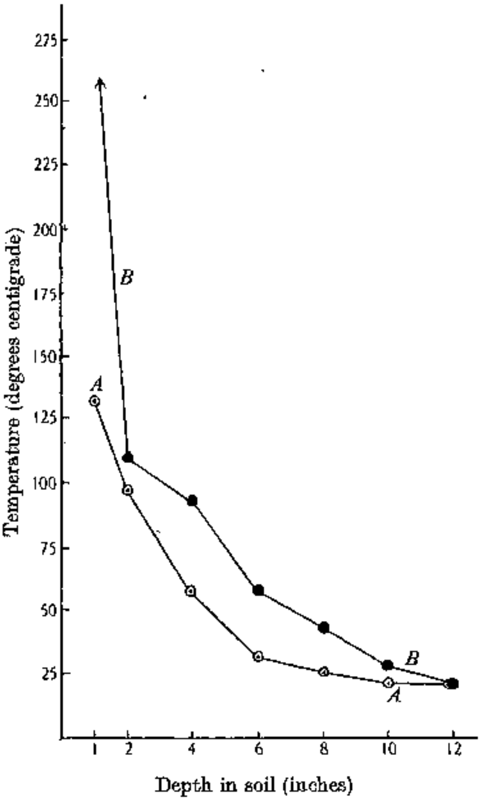

Fig. 3.

Fig. 2. Water content of the soil before and after fire, plotted against depth in soil. *A*, "wet" soil before fire; *B*, "dry" soil before fire; *C*, "wet" soil after fire; *D*, "dry" soil after fire.
Fig. 3. Soil temperature during fire plotted against depth in soil. *A*, "wet" soil; *B*, "dry" soil.

Table 5. *Physical properties of soil before and after fire*

	*p*H		Water-retaining capacity		% Loss on ignition	
Community	Unburned	Burned	Unburned	Burned	Unburned	Burned
Dry scrub	5·0	5·0	44	38	7·6	4·4
	4·7	4·5	48	42	12·8	8·6
Eucalyptus forest	5·4	5·0	32	29	2·9	2·7
	5·1	5·0	31	29	3·1	2·9
Moist scrub	5·2	4·8	31	28	1·8	1·8
	5·1	4·6	38	30	3·3	2·6
Moss mat	4·9	4·9	40	38	7·1	7·0
	4·6	4·6	56	55	4·9	5·1

C. *Discussion*

If the soil were quite dry and were a homogeneous system, the relationship between temperature and depth would be exponential. But the agreement with an exponential relationship is not close for two reasons: (1) there is a heterogeneous distribution of water in the soil, and (2) at a temperature above 100° C. heat would be utilized to overcome the latent heat of vaporization of water. Therefore there is an unconformity in the curve at this point.

The result of the application of a source of heat at the surface is the desiccation of the surface layers of the soil, so that the system becomes heterogeneous, consisting of an upper dry zone with a relatively high conductivity and a lower zone with a higher water content and therefore a lower conductivity. The logarithmic curves (Fig. 4) exhibit a steep slope near the surface, indicating a rapid conduction of heat by the desiccated surface layers. The remainder of the logarithmic curves are, in every case, a first approach to a straight line, indicating a homogeneous "wet" system.

III. SURVIVAL OF VEGETATION

The foregoing sections show that considerable temperatures are reached in the soil during fire, especially in dry soil, even at a depth of 6 in. In spite of such unfavourable conditions, it is characteristic of *Eucalyptus* forests that after fire regeneration of woody plants is common and dense mats of seedlings appear from seed which has survived the fire.

A. *Regeneration of woody plants*

Unlike the forests of the Northern Hemisphere, the *Eucalyptus* forests of Australia are not killed by fire and are therefore capable of regeneration from subaerial and subterranean shoots. The modes of regeneration of woody plants are:

(*a*) Shoots from the trunk and branches (epicormic shoots).

(*b*) Shoots from lignotubers.

(*a*) Since many Australian trees have a thick bark and therefore well-insulated meristematic layers in which cortical buds are buried (Jacobs), they readily produce shoots from the trunk and branches (Pl. 1A). Even shrubs which are more easily destroyed, may produce shoots from cortical buds in charred aerial stems, e.g. *Angophora cordifolia*, *Leptospermum stellatum*.

(*b*) Most remarkable of all is the regeneration from lignotubers which have been described in *Eucalyptus* by Kerr (1925) and Carter (1929). These structures are a peculiar feature of many Australian plants and are most common in the Myrtaceae and Proteaceae (Fig. 5 and Pl. 1 B, C), and are entirely lacking in the Leguminoseae, Rutaceae, Casuarinaceae and most Epacridaceae.

A. Regeneration from subaerial shoots in *Eucalyptus*.

B. Lignotuber of *Lambertia formosa* (Proteaceae) showing the lateral development of subaerial shoots.

C. Development of the lignotuber in seedlings of *Banksia latifolia* var. *minor* (Proteaceae).

An examination of the plants which survive a natural fire shows that the species with lignotubers are rarely killed, while regeneration of plants which do not possess lignotubers is not common (Table 6). The depth below the surface of a lignotuber will be of great importance in its survival. Table 6 gives the location of some of these organs in the soil. From these figures it can be seen that lignotubers are frequently large organs and that they are usually buried sufficiently deeply to avoid high temperatures. Therefore the charring of the top of a lignotuber may occur without causing the death of the plant (Pl. 1 C).

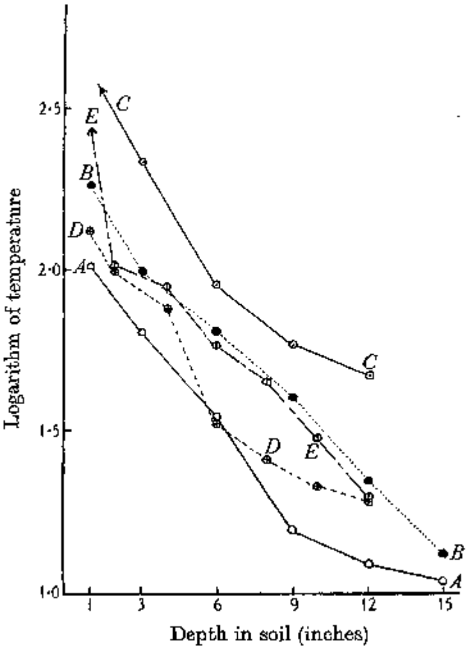

Fig. 4.

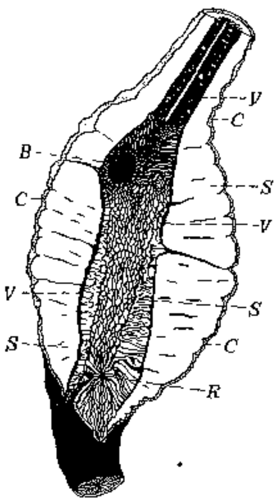

Fig. 5.

Fig. 4. Logarithm of temperature plotted against depth in soil. *A*, from curve *A*, Fig. 1; *B*, curve *B*, Fig. 1; *C*, curve *C*, Fig. 1; *D*, curve *A*, Fig. 3; *E*, curve *B*, Fig. 3.

Fig. 5. Longitudinal section of the lignotuber of *Banksia serrata* (Proteaceae). *V* = vascular tissue; *S* = starch storage tissue; *C* = cork; *R* = section through a large lateral root; *B* = section through a branch. $\frac{1}{4}$ natural size.

B. *Development of seedlings*

Notwithstanding the possibility of destruction or inactivation of seed by fire, the number of seedlings which appears in a burned area far exceeds the number in an unburned area of the same dimensions (Table 7).

These figures show that there is a significant increase in the number of seedlings after fire in all communities, the increase being most conspicuous in moist communities (moist scrub and moss mats). This point is further emphasized by the figures quoted in Table 8, which show that there is a

Table 6. *Location in the soil of some lignotubers and the percentage survivors of species with and without lignotubers*

Name	Lignotuber Presence + Absence −	Depth in soil (in.) Upper surface	Lower surface	Percentage of plants which survive fire
Angophora cordifolia	+	0	9	100
Banksia latifolia var. *minor*	+	0	5	100
B. serrata	+	0	8–9	100
B. spinulosa	+	0	5–6	100
Hakea dactyloides	+	0	5	100
Leptospermum stellatum	+	0	6	100
Lomatia salaifolia	+	4	8	100
Petrophila pulchella	+	2	4	92
Banksia ericifolia	−	.	.	12
Casuarina rigida	−	.	.	0
Hakea gibbosa	−	.	.	0
H. pugioniformis	−	.	.	0
Leptospermum scoparium	−	.	.	0

Table 7. *Number of seedlings before and after fire. Counts done in same general locality, on same day,* 5 *months after fire*

	Number of seedlings per sq. m.			
	Burned		Unburned	
Community	Mean	σ	Mean	σ
Eucalyptus forest	27	13·4	4	1·7
Moist scrub	342	222·0	7	3·7
Dry scrub	19	8·2	4	2·4
Moss mat	Over 1000	—	32	13·6

Table 8. *Water content of the soil and seedling frequency* 5 *months after fire. All soil samples were collected, and all counts were done on the same day, no rain having fallen for the last month*

Community	Percentage soil moisture calculated on oven-dried (110° C.) soil	Number of seedlings per sq. m.
Moss mat	47·4	700–800
	51·9	approx. 800
Moist scrub	26·8	240
	31·3	280
Eucalyptus forest	5·1	25
	8·8	51

definite relationship between the water content of the soil and the number of seedlings.

The development of these large numbers of seedlings can be attributed to (*a*) the dehiscence of woody fruits, and (*b*) the ability of the seeds to resist high temperatures.

(*a*) *Dehiscence of woody fruits.*

Many species, particularly members of the Proteaceae, Myrtaceae and Casuarinaceae, possess hard, woody fruits which remain attached to the plant for years after the seed is mature. The retention of the seed on the plant is not an essential process since the fruits on heating over a flame liberate their seeds, which are viable. The advent of a fire causes the simultaneous dehiscence of these fruits, so that the number of viable seeds liberated after fire is very large (Table 9), whereas under natural conditions, since the fruits do not dehisce, the frequency of the seed in the soil is relatively low.

Table 9. *Potential seed production per plant of some plants which produce woody fruits*

	Potential seed production per plant	
Name	Maximum recorded	Mean for 10 plants
Banksia ericifolia	2,900	2,300
B. serrata	5,000	2,500
B. latifolia var. *minor*	930	560
Casuarina rigida	83,000	54,000
Hakea gibbosa	150	80
H. pugioniformis	1,200	800
Leptospermum scoparium	106,000	49,000
Petrophila pulchella	13,000	4,600

(*b*) *Resistance of seeds to high temperatures.*

The seeds of all species investigated are relatively resistant to high temperatures when compared with such seeds as those of wheat, sunflower or peas. Table 10 gives the percentage germination, after treatment at various high temperatures in the dry state, of a few common species. These figures show that a temperature of 110° C. for 4 hr. does not greatly reduce the percentage germination, while a few seeds can withstand a temperature of 120° C. or even 130° C. for the same time.

Table 10. *Percentage germination of seeds after subjection to various high temperatures in the dry condition for 4 hr.*

			Percentage germination after treatment for 4 hr. at (° C.)							
Name	Testa H = Hard S = Soft	Normal percentage germination	60	70	80	90	100	110	120	130
Acacia decurrens	H	98	—	—	—	98	72	Nil	—	—
Angophora lanceolata	S	98	—	—	—	—	98	90	16	Nil
Callistemon linearis	S	30	—	—	—	—	30	22	20	4
Casuarina rigida	S	57	—	—	—	—	57	47	Nil	—
Eucalyptus gummifera	S	92	—	—	—	—	92	90	Nil	—
Hakea acicularis	S	100	—	—	—	—	100	88	Nil	—
Leptospermum scoparium	S	25	—	—	—	—	—	25	16	Nil
Peas	S	100	100	84	11	Nil	—	—	—	—
Sunflower	S	100	100	15	Nil	—	—	—	—	—
Wheat	S	100	—	—	100	79	Nil	—	—	—

Since the seed involved in the replacement of the communities is present in the soil before the fire or is liberated from the fruit immediately after the fire, the soil temperature and that within the fruit will be important with reference to the survival of seed during fire. The probable maximal soil temperature at a depth of 1 in. is about 112° C. (Fig. 1, curve *A*), which temperature was reached after the fire had been burning for 2 hr. Therefore seeds which will withstand a temperature of 110° C. for 4 hr. will certainly survive if buried at a depth of 1 in. Also the hard woody fruits, common to many species, act as insulating layers, protecting the seeds during fire.

Not only will the seeds be subjected to high temperatures in the dry state, but also to the action of hot water and steam. Seeds whose testas are permeable to water at any temperature (soft seeds), have a low resistance to high temperatures in the wet condition, comparable with that of peas, sunflower or wheat (Table 11). On the other hand, hard seeds (Rees, 1910, 1911), i.e. those whose testas are impermeable to water at room temperature (18–20° C.), may be subjected to high temperatures in the wet condition for relatively long periods without injury (Table 12). On the contrary, the permeability of the testa is increased so that the percentage of seeds capable of immediate germination is greatly increased.

Table 11. *Percentage germination of seeds after immersion in hot water at various temperatures for* 5 *min.*

	Percentage germination after immersion in water for 5 min. at (° C.)			
Name	50	60	70	80
Peas	100	100	70	Nil
Wheat	100	Nil	—	—
Sunflower	100	100	Nil	—
Hakea acicularis	100	100	100	Nil
Casuarina rigida	57	57	40	Nil
Leptospermum scoparium	25	25	16	Nil
Banksia serrata	100	100	100	Nil

Table 12 gives the results obtained by boiling the seeds of *Acacia decurrens* for various times. The number of seeds which swells during boiling is approximately constant for the different times (Table 12, column 2), showing that the permeability of the testa is independent of the time of boiling. The seeds which swell during boiling are killed, thus behaving similarly to soft seeds. The remainder, after removal from the boiling water, are apparently hard. After 24 hr. the total number of seeds which have imbibed water is 53–70 %, while after 6 days 84–97 % have swollen. After 10 days the testas of all the seeds are permeable. The percentage germination decreases with the time of boiling (Table 12, column 5 and Fig. 6). Boiling for 5 min. reduces the percentage germination from 98 to 63 %, while after boiling for 70 min. the percentage germination is reduced to 3 %.

This remarkable resistance to the action of boiling water can be attributed to the ability of the testa to exclude water from the embryo. The testa itself, though apparently impermeable after removal from boiling water, becomes permeable within 10 days, thereby enabling the seeds, which were incapable of germinating under natural conditions, to germinate.

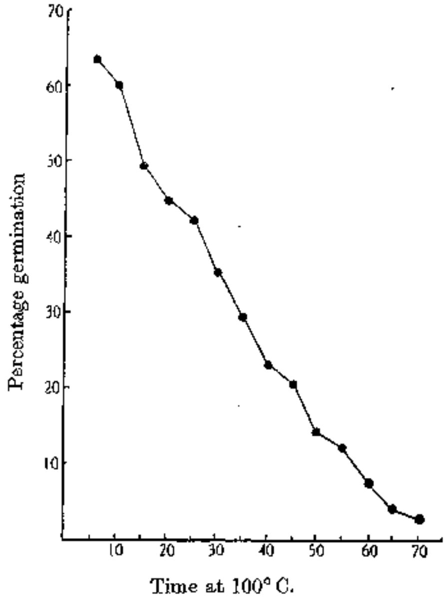

Fig. 6. Percentage germination of hard seeds plotted against time of boiling.

Table 12. *The effect of boiling on the permeability of the testa and percentage germination of the seeds of* Acacia decurrens

Time at 100° C. min.	% of seeds which swell during boiling	% of seeds which swell after 24 hr.	% of seeds which swell after 6 days	Total % germination
5	21	64	92	63
10	15	58	90	60
15	17	62	87	49
20	18	53	84	45
25	15	57	91	43
30	23	62	88	36
35	20	62	91	29
40	13	59	93	23
45	19	54	93	21
50	27	62	96	14
55	23	62	97	12
60	24	61	95	7·5
65	25	70	96	4·5
70	25	65	95	3
Control	—	2	2	98

IV. SUMMARY AND CONCLUSIONS

A method for measuring soil temperatures during forest fires is described and data are given showing the temperatures under various conditions.

During natural fires on the sandstone of the central coastline of New South Wales, the surface temperature varies from 81 to 213° C. At a depth of 1 in. the temperature does not exceed 67° C.

The probable maximal temperature during a severe fire at a depth of 1 in. is 111–114° C.; at 3 in. 59–67° C. Below this level, the soil temperature is not sufficiently high for a long enough period to harm plant organs.

Under extreme conditions (if trees were entirely burned), the temperature at a depth of 1 in. exceeds 250° C., while at a depth of 1 ft. the temperature is 43–50° C.

High percentages of water in the soil greatly retard the conduction of heat. There is not a redistribution of water in the soil after fire; the water is lost to the atmosphere and does not pass downwards and condense.

Fires have no appreciable effect on the physical properties of the soils investigated.

Fires do not kill the vegetation, but many woody plants are capable of regeneration from aerial stems and lignotubers. Plants which possess lignotubers are rarely killed.

After fire, the number of seedlings which appears is very large. This can be attributed to the desiccation and dehiscence of woody fruits and to the ability of the seeds to resist high temperatures.

The seeds of all native plants investigated can resist a temperature of 110° C. for 4 hr. in the dry condition.

The effect of high temperatures on seeds in the wet condition is discussed. Soft seeds are killed after immersion for 5 min. in water at 60–80° C. Hard seeds can withstand the temperature of boiling water for as long as 70 min. when the percentage germination is reduced from 98 to 3%. Boiling water increases the permeability of the testa, thereby enabling the seed to germinate.

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