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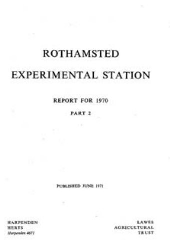
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Soil Fumigation and Root-rots of Wheat

G. A. SALT

That fumigating soil could increase the yield of cereals was first shown at Rothamsted early this century when Russell and Hutchinson (1909) reported increases ranging between 20 and 50% in yield from plants grown in pots containing soil treated with toluene; responses they attributed to enhanced bacterial activity that increased the mineralisation of plant nutrients. However, in the field, carbon disulphide, toluene and formalin gave disappointingly small and inconsistent yield increases, which Russell (1914) attributed to the difficulties of fumigating soils efficiently in the field. The importance of soil-borne pathogens was only realised later, when Russell turned his attention to studying soil sickness of glasshouse soils, and got such improved growth after partial sterilisation that this was soon adopted as a standard practice.

The reason for resuming work on soil fumigation for cereals, after a lapse of 50 years, was given by Widdowson and Penny (1970), who used formalin drenches to try and gain information on the reason for cereal crops on some light soils promising well at first but failing during dry weather in June. In 1964 formalin trebled yields of spring wheat at Woburn, and greatly decreased the incidence of take-all *Ophiobolus graminis* Sacc. and cereal cyst nematode *Heterodera avenae* (Slope, 1966; Williams, 1969). In 1965 this work was extended to the heavier soil at Rothamsted, where take-all is sometimes severe, but where cereal cyst nematode and summer drought are much less harmful than at Woburn. Widdowson and Penny (1970) discussed both the effects of formalin and nitrogen fertiliser on the yields and N contents of spring and winter wheats, of barley and of grass. This paper describes the effects of these treatments on take-all and other fungal diseases in the wheat crops.

Methods and materials

The experiments were on adjacent fields, Little Knott, where 19 crops of cereals had been grown during the past 21 years, and Pastures, which had been in grass for ten years before it was ploughed and sown with spring wheat in 1964. The treatments, described in detail by Widdowson and Penny (1970) and Salt (1969), were formalin (266 gal of 38% formaldehyde in 4000 gal water/acre) applied by watering can, and four different amounts of calcium nitrate (Table 1). Spring wheats were sown in 1965 (Opal) and 1966 (Kloka), and in 1966 plots were such that effects of formalin applied in 1965 or 1966 could be compared with effects of applying it in both years or neither. In 1966 formalin was also applied during the autumn, before sowing winter wheat (Cappelle), again to plots that allowed residual effects to be compared with effects of newly applied formalin. In 1967 treatments were again applied during autumn before sowing Cappelle, but on Little Knott it was no longer possible to have plots that were given formalin each year or that had never had formalin. Samples, each containing about 50 plants from four separate 6-inch lengths of drill, were taken from each plot three times between April and July. After washing, each plant was scored for presence or absence of take-all, eyespot (*Cercosporella herpotrichoides*), sharp eyespot (*Rhizoctonia solani*), brown foot rot

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TABLE 1

Percentages of straws with roots infected by take-all in July 1965–68

Year	1965		1966				1967				1968			
Formalin	O	F	O	F	F	F	O	F	F	F	O	F	F	F
			1965 1966	1965 —	— 1966	1965 1966	1966 1967	1966 —	— 1967	1966 1967	1967 1968	1967 —	— 1968	1967 1968
Cwt N/acre							Little Knott total infection							
0·0	99	38	96	100	19	46	74	100	77	100	64	100	73	98
0·5	92	30	77	94	12	30	84	98	48	86	36	85	56	50
1·0	92	24	49	90	0	11	61	98	66	96	18	68	97	40
1·5	91	38	62	86	4	25	60	100	62	87	13	53	80	41
							Little Knott severe infection							
0·0	69	9	44	90	7	28	7	94	35	34	28	56	26	30
0·5	55	9	44	72	12	3	26	74	2	75	4	19	27	9
1·0	38	4	13	59	0	3	0	28	36	50	0	23	47	12
1·5	52	15	33	54	0	17	2	69	6	26	0	13	45	0
							Pastures total infection							
0·0	6	0	84	62	15	27	92	96	74	54	31	29	32	57
0·5	0	0	54	59	28	32	69	100	71	81	32	65	55	56
1·0	0	6	42	50	46	16	76	84	51	80	72	33	19	30
1·5	0	0	46	34	5	10	69	100	88	78	13	76	76	54
							Pastures severe infection							
0·0	4	0	62	33	5	18	32	61	20	19	10	8	12	18
0·5	0	0	32	40	10	27	16	78	20	56	15	32	28	30
1·0	0	0	14	40	35	6	37	6	30	54	40	11	10	13
1·5	0	0	12	26	1	4	33	68	48	20	5	32	48	32

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(*Fusarium*), brown root rot (*Pythium*) and abnormal proliferating roots (*Heterodera avenae*). Severe take-all, affecting more than half of the root system sampled, was also recorded.

Results

Take-all on Little Knott, 1965–68. Formalin greatly decreased the incidence of take-all in June 1965 and its effect persisted and increased until harvest (Fig. 1). Nitrogen had no consistent effect on the proportion of infected or severely infected plants (Table 1), but greatly increased yields (Widdowson & Penny, 1970).

Formalin applied in 1966 decreased take-all even more than it had done in 1965, but less where it was also given in 1965 than where not. Where it was used in 1965 and not again in 1966, take-all was more prevalent and severe than where it had not been used at all (Fig. 1). Nitrogen greatly decreased both total and severe take-all, and decreased it most where formalin had not been applied in either year. Take-all was negligible with formalin plus 1·0 cwt N/acre in 1966, and grain yield averaged 42·5 cwt/acre, whereas with formalin in 1965 and no extra nitrogen in 1966, 90% straws were severely infected (Table 1) and yield averaged only 13·0 cwt/acre.

Formalin applied after ploughing in September 1966 decreased take-all in the winter wheat crop, but did not where applied to the stubble before ploughing (Fig. 2) and the mean effect, in contrast to previous years, was not significant. Where formalin was applied for the previous crop take-all was severe, and without extra N the crop almost failed, yielding only 4·4 cwt grain per acre. Nitrogen greatly increased grain and straw yields (Widdowson & Penny, 1970) but had no consistent effect on the incidence or severity of take-all (Table 1). Plots given formalin in 1966 and 1967 had more take-all and smaller yields than those without formalin in either year.

Formalin applied in September 1967 before sowing winter wheat decreased take-all next May, but later the disease developed more in fumigated plots, so that by harvest fumigation had increased disease incidence and severity (Fig. 1). A large increase in take-all after formalin in the previous season was evident on 2 May and remained until harvest. The most severe disease and smallest yield (17·5 cwt/acre) was again in unmanured plots treated with formalin in the previous season (Table 1). Nitrogen decreased the incidence and severity of disease, except where formalin was newly applied.

Formalin controlled take-all much better when applied in February before spring wheat than when applied in September before winter wheat. By contrast, the deleterious effect of formalin applied before the previous crop was as great, or greater, in winter as in spring wheat. This deleterious effect persisted for only one season, and where formalin was applied 2 or 3 years earlier there was less take-all and slightly larger yields than where it had not been used, but these differences were not significant at the 5% level.

Take-all on Pastures, 1965–68. Pastures soil was rich in nitrogen, and formalin and nitrogen affected yield much less than in Little Knott (Widdowson & Penny, 1970). Not only did plots without extra N yield much more than on Little Knott, but the potential benefit from formalin and nitrogen was lost because of lodging. In 1965 the spring wheat on Pastures had scarcely any take-all and the only benefit from formalin was a small increase in straw. Take-all occurred in the 1966 spring wheat crop, and its incidence was much decreased by formalin. In contrast to Little Knott, take-all was not increased by formalin applied in 1965 (Fig. 1). Nitrogen decreased the incidence and severity of infection (Table 1) especially in unfumigated soil, but yields were limited by lodging and were not increased by more than 0·5 cwt N/acre.

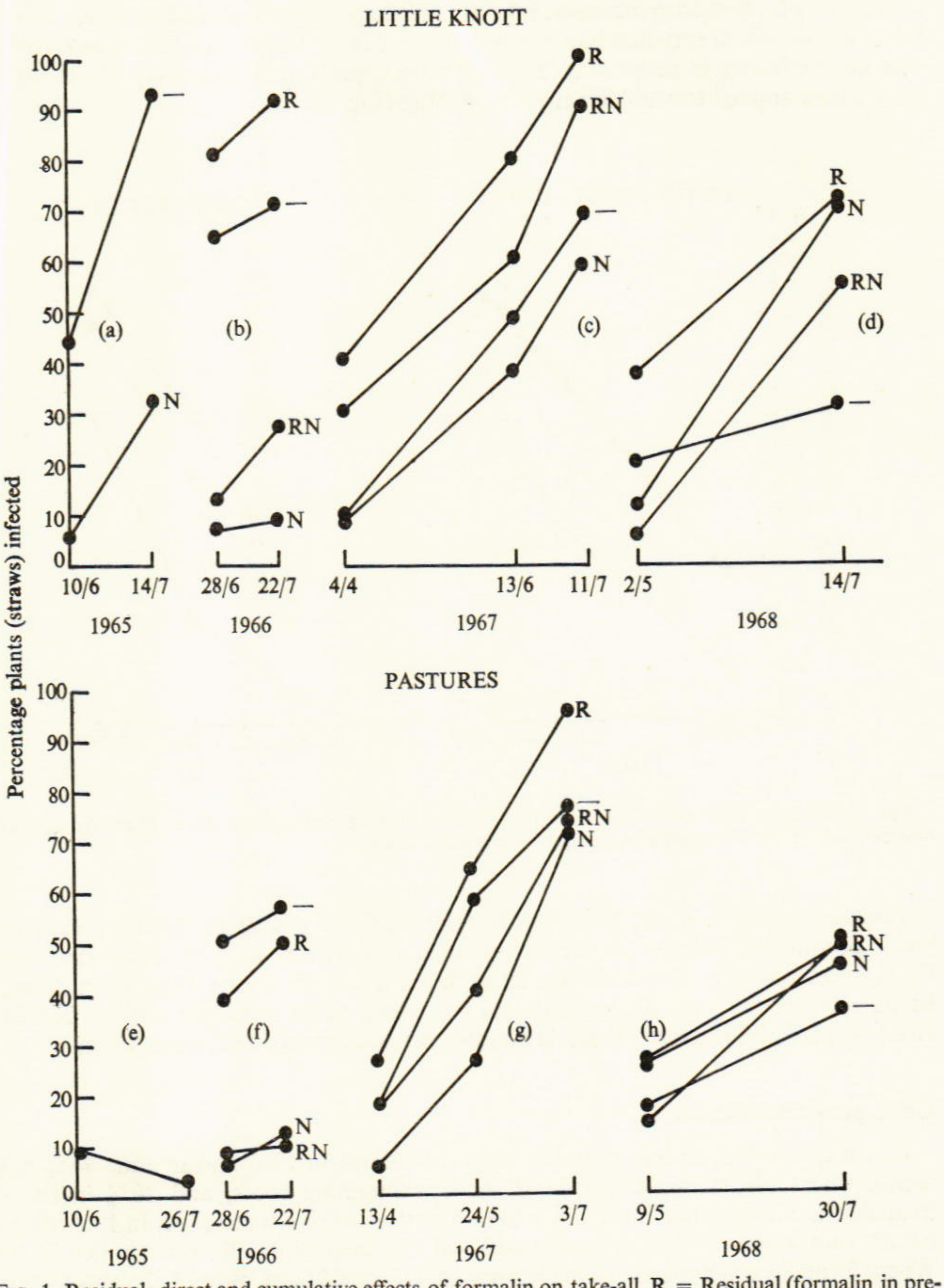

FIG. 1. Residual, direct and cumulative effects of formalin on take-all. R = Residual (formalin in previous year); N = New formalin in harvest year; RN = Formalin in previous and harvest year; — = None in harvest or previous year.

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In 1967 formalin affected take-all on Pastures as on Little Knott. Formalin applied before the previous crop increased take-all and depressed yields, and nitrogen decreased take-all only where formalin had not been given (Table 1). As on Little Knott, formalin was more effective in decreasing take-all where applied after ploughing and cultivating than where applied to stubble before ploughing (Fig. 2).

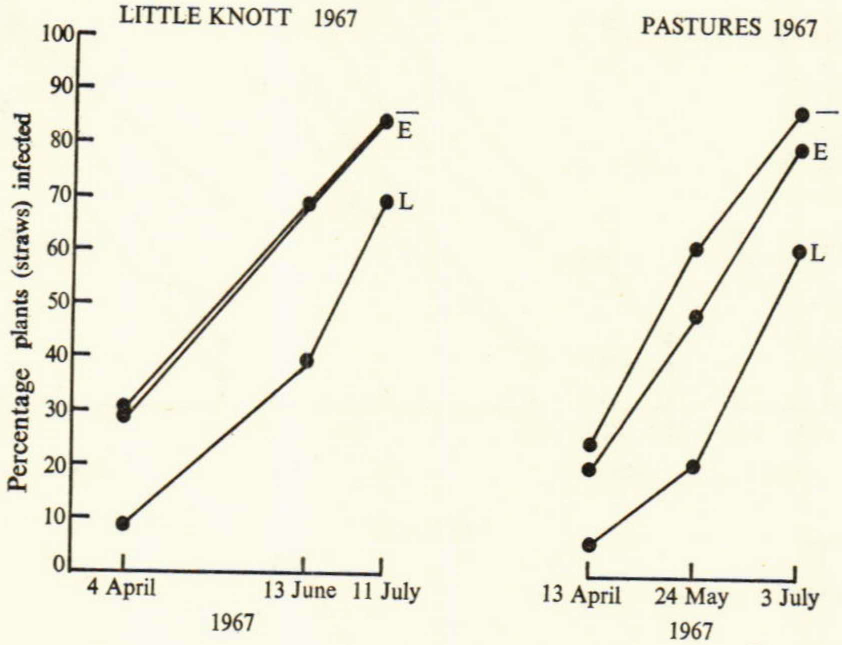

FIG. 2. Effect on take-all of formalin applied before and after ploughing. E = Formalin applied to stubble; L = Formalin after ploughing; — = No formalin.

Formalin applied in autumn 1967 had little effect on take-all but decreased grain yield, presumably because in the wet summer it increased lodging. Formalin applied for the previous crop increased take-all at harvest, but also increased yield, presumably because the poorer crop lodged less and so yielded more. Nitrogen had no consistent effect on take-all incidence (Table 1) and 0·5 cwt N/acre gave the largest yield.

Other pests and diseases

Cereal cyst nematode was prevalent on Little Knott in 1965 and in June 44% of the spring wheat plants in untreated soil had proliferating roots, and 20% in formaln treated soil. Nitrogen had no effect on the proportion of plants attacked. In 1966 attacked plants were fewer, 19% in untreated soil and 1% where formalin was applied in 1966. Where formalin was applied in 1965 but not again in 1966 there were 27% plants attacked, and 5% where formalin was applied in 1965 and 1966. These effects of formalin on *H. avenae* populations repeat those in the spring wheat at Woburn (Williams, 1969). *H. avenae* was less prevalent in the winter wheat on Little Knott in 1967 and 1968, and was not found in wheat on Pastures.

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Cercosporella herpotrichoides. Fewer plants were infected in Pastures than on Little Knott, and the percentages of straws infected by July were decreased by formalin (Table 2). In 1967 the drenches on stubble and after ploughing both decreased the amount of infection. In contrast to take-all and eelworm, eyespot was not increased by formalin applied for the previous crop; nitrogen had no consistent effect on eyespot.

TABLE 2

Percentage straws with eyespot

	July 1965	July 1966	April 1967	July 1967	July 1968
Little Knott					
No formalin	31	14	29	37	34
Formalin to stubble	—	—	19	37	—
Formalin after ploughing	12	3	15	31	27
Pastures					
No formalin	2	7	8	37	18
Formalin to stubble	—	—	7	15	—
Formalin after ploughing	1	1	7	24	13

Rhizoctonia solani affected fewer than 5% of the straws except in 1967 on Pastures, when 12% were infected in plots not treated with formalin, 8% where it was applied before ploughing, and 1% where it was applied after. Nitrogen had no effect.

Brown foot rot *Fusarium roseum* was also uncommon except in July 1967, on Little Knott, where 0·0, 0·5, 1·0 and 1·5 cwt N/acre gave 10, 14, 24 and 34% infected straws. Formalin had no effect.

Brown root rot was of two types. In one the roots were pale brown, watersoaked and many were filled with *Pythium* oospores. Most of the rotted portion was usually missing, leaving a tapering brown tip to the affected root. Pythium root rot was usually unaffected by nitrogen fertiliser or formalin. It was most prevalent in Little Knott during April 1967, when an average of 23% plants had a few roots infected, but usually fewer than 5% of plants were infected. The other form of root rot was more extensive and darker brown. Brown roots remained attached and did not contain oospores. *Fusarium avenaceum* and *Fusarium* (*sp.*), probably *F. tricinctum* were usually isolated. Usually few plants were affected, but the proportion increased with each increase in amount of nitrogen fertiliser and where formalin was applied. For example, on Little Knott in May 1968, 6, 21, 18 and 32% plants were affected in untreated, and 6, 30, 43 and 53% in formaldehyde-treated plots given 0·0, 0·5, 1·0 and 1·5 cwt N/acre respectively. This unusual prevalence on roots during May was not followed by brown rot of straw bases in July, which was wet and not expected to favour the development of brown foot rot symptoms. Except for cereal cyst nematode on Little Knott in 1965, these other diseases were of minor importance compared with take-all, and probably did not affect yields greatly.

Discussion

Effects of formalin on take-all are closely correlated with those on yield (Widdowson & Penny, 1970), with less take-all and increased yield in the first crop after application, but less yield and much more take-all when a second wheat crop is taken next year. Applying formalin for successive crops did not decrease take-all as much as the first application.

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Widdowson and Penny showed that formalin increased the amount of nitrogen assimilated by the crop, whether or not root pathogens were abundant. The amount of extra nitrogen assimilated was unexpectedly large; for example, on Little Knott in 1965 and 1966 the effect of formalin was approximately equivalent to giving wheat 1·0 cwt more N/acre. This benefit was probably derived partly from the healthier wheat using the reservoir of soil nitrogen more efficiently, and partly from the additional nitrogen mineralised by partial sterilisation of the soil (Gasser & Peachey, 1964; Jenkinson & Powlson, 1970; Williams & Salt, 1970).

The decreasing responses in yield to repeated formalin treatments were explained, partly at least, by Jenkinson and Powlson (1970), who found that soil from Pastures mineralized less nitrogen after a second than after the first fumigation, presumably because fumigation exhausts the reserves of nitrogen contained in living soil organisms. Thus, when nitrogen limits crop growth, a second fumigation will be less effective than the first in increasing yield, apart from any effect on plant pathogens. This difference between fumigated and unfumigated soils persists, for it was not only observed in Pastures soil three years after fumigation, but also in Butt Close soil, Woburn, five and a half years after treatment with formalin, and in Broadbalk 22 months after treatment with methyl bromide (Jenkinson & Powlson, 1970). In contrast to this persistent effect of fumigation on soil nitrogen reserves, there is evidence that the flush of additional mineral nitrogen released by fumigating field soils with various chemicals lasts only a matter of weeks, and is barely detectable after six months (Ebbels, 1968; Jenkinson & Powlson, 1970).

The extent to which soil nitrogen is exhausted by the crop taken after fumigation is shown dramatically on Little Knott by the near failures on unmanured plots, and the greatly improved yield on plots given increasing amounts of nitrogen fertiliser. On Pastures, with much larger nitrogen reserves, the residual effect of previous fumigation was much less harmful.

In addition to the depletion of nutrients, severe take-all also contributed to small yields by the second crop after fumigation. Lack of nutrients does itself increase the severity of take-all, but it seems that there must be other reasons for the take-all fungus developing so rapidly in the second crop after fumigation. It is easy to suggest that fumigation destroys antagonists that usually hold the pathogen in check, but this is difficult to prove. Winter (1942) showed that the growth of runner hyphae along wheat roots was stimulated by heating the soil or treating it with chloroform, sulphur dioxide, alcohol or tolulol, and he concluded that this stimulation resulted from the elimination of antagonistic organisms, which were restored to treated soils by inoculation with small amounts of unsterilised soil. Henry (1932) also concluded that antagonists to *O. graminis* were responsible for the disease rating of wheat seedlings decreasing in unsterilised but increasing in autoclaved soil as the temperature was raised from 13°C, where the disease rating was similar for both soils.

Fumigation behaves much as does introducing into a succession of cereal crops a crop that is not susceptible to take-all. There are much greater yields (with less fertiliser) and much less take-all in the next cereal than without any break from cereals, but smaller yields and more take-all in the succeeding crop than where cereals were grown continuously.

Suppressing organisms that inhibit the growth of the take-all fungus could explain some of the results of our experiments. However, for others it seems that the effects of formalin are rather on the extent to which the fungus survives in soil, and that the fungus has a greater chance of surviving between crops in fumigated than in unfumigated soils.

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Fumigation might aid the survival of the fungus in several ways. One could be by slowing the decomposition of crop residues, either because the crop is larger and removes more nitrogen from the soil, or because the soil saprophytes are fewer. Inoculum of the take-all fungus may be less effective from many diseased plants that die prematurely with rotted roots than from fewer plants that survive with larger slightly infected root systems.

It is worth comparing formalin with other fumigants used on field soils. Formalin and dazomet were better than chloropicrin, methyl bromide or 'D-D' in controlling take-all in spring wheat at Woburn (Williams & Salt, 1970), but formalin was the least effective in controlling nematodes. Except for 'D-D', all fumigants increased take-all in the second wheat crop grown the year after they were applied, but none by as much as formalin did. However, the adverse effect was counteracted by giving 1·8 cwt N/acre. It seems that it may be a common feature of fumigants that control take-all when first applied, to increase it in succeeding cereal crops, and for this deleterious effect to be decreased by applying more nitrogen fertiliser. The development of take-all in crops sown after soil fumigation must depend partly on the efficiency of the fumigant in killing the pathogen in crop debris in the soil. Ebbels (1970) showed that, in columns of soil in plastic tubes, only some of the mycelium in buried wheat straw was killed by fumigation. Formalin applied to the soil surface killed more *O. graminis* in the top 30 cm (12 in.) than in the 30 to 60 cm (12 to 24 in.) zone, where the fungus survived in more than half the pieces of straw. Chloropicrin injected at 15 cm (6 in.) killed more *O. graminis* than formalin in the top half of the columns but killed no more at greater depth. 'D-D' mixture had comparatively little effect and killed *O. graminis* inoculum for only a short distance below the point of injection at 15 cm (6 in.). Soil compaction and temperature in the soil columns probably differed from those in the field so extrapolation from these results must be done cautiously. However, fumigation in tubes of sieved soil is probably more efficient than in the field, and the results indicate that much of the take-all fungus in field soil may survive fumigation. The earlier wheat is sown the greater are its chances of becoming infected from viable fungus at greater soil depths. This would help to explain the poor control of take-all in winter wheat by formalin applied after ploughing, and the failure to achieve any control where applied before ploughing.

In two other experiments made at Rothamsted, fumigation failed to give the same control of take-all in winter wheat as described here with spring wheat. On Broadbalk methyl bromide applied under polythene sheets during October improved growth and decreased take-all in April, but by July there were more take-all infected plants in fumigated than in unfumigated soil (Salt & Corbett, 1969). On Claycroft field, formalin and dazomet both decreased take-all in April but the proportion of severely infected plants at harvest was decreased significantly only by dazomet (Ebbels, 1971).

Soil fumigation has largely failed to control other soil-borne diseases of cereals. Formalin was the only fumigant to decrease eyespot infection, probably because the way it was applied ensured its contact with superficial crop debris, which is the main source of infection (Cox & Cock, 1962). Ebbels (1970) confirmed this explanation by raking straw from treated and untreated plots at Rothamsted, and showing that the percentage of infective pieces was decreased by formalin but not by dazomet or 'D-D'. None of the fumigants tested decreased brown foot rot caused by *Fusarium roseum*, or brown root rot caused by *Pythium* spp. The survival of *Pythium* in crop debris or as resting spores in soil has not been recorded, but formalin or dazomet killed *F. roseum* in only one-third of the superficial pieces of straw (Ebbels, 1970). This suggests that the source of *Fusarium* infection, as of *C. herpotrichoides*, is mainly from surface litter. In forest nurseries, where the whole crop including most of the roots is removed each year,

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and where the light sandy soil is easily fumigated, formalin and dazomet both prevent *Fusarium* and *Pythium* infection of coniferous seedlings (Warcup, 1952; Salt, 1965). Failure to kill pathogens in agricultural soils is probably a mechanical problem of inefficient distribution of fumigant, rather than ineffectiveness of the chemicals, and sealing the soil surface with a plastic sheet after applying the fumigant would probably help to kill more fungi in the surface litter, where lethal concentrations of fumigant are difficult to maintain.

These results gave little hope of soil sterilants being used economically to control soil-borne diseases in intensive cereal growing, unless larger benefits can be obtained from cheaper materials. However, where cereals are grown in rotation with other crops, especially those producing larger returns per acre and susceptible to nematodes or fungi, there could be considerable benefit, for crops can benefit from a fumigation given some years earlier.

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