INCIDENCE AND PATHOGENICITY OF *FUSARIUM* SPECIES ASSOCIATED WITH TEMPERATE CEREALS IN EAST SCOTLAND

by

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DEDICATION

Quiero dedicar esta tesis a mi esposa, Paty, e hija, Yaffar Dwaimy, quienes me han brindado su cariño y comprensión durante estos tres años.

También quiero dedicar esta tesis a mis queridos padres, Jesús y Consuelo, quienes me enseñaron el valor de la fe y esfuerzo cotidiano.

DECLARATION

This is to declare this thesis has been carried out by myself and has not been accepted for any previous application for a degree. All information and assistance obtained from other sources has been acknowledged in the appropriate places.

Manuel Rosas Romero
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ABSTRACT

In a survey of the incidence of *Fusarium* species on plants from cereal, fungicide-trial plots in the east of Scotland, carried out in 1987 and 1988, *F. culmorum* was the most prevalent pathogenic species and *F. dimerum* the most frequently occurring saprophyte. The former species was generally distributed over roots, stems and ears but *F. dimerum* was confined to roots and stems. High infection levels of other pathogens, *F. avenaceum* and *F. nivale*, and of the weak pathogens, *F. poae* and *F. sambucinum*, were found only sporadically. *Fusarium* species occurring in slight or traces amounts included, *F. graminearum, F. moniliforme,* recognized pathogens of cereals, *F. equiseti, F. sporotrichioides* and *F. tricinctum*, weak pathogens, and *F. acuminatum, F. oxysporum, F. semitectum, F. solani and F. sulphureum* which are non-pathogenic to cereals. Fungal genera, other than *Fusarium*, which were prevalent included *Cylindrocarpon* on roots, *Mucor* on stems and *Cladosporium* on ears. *Trichothecium roseum* was frequent in some crops and attracted interest as a potential antagonist of *Fusarium* and as a potential plant pathogen. Fungicide treatments applied to plots to control mainly cereal leaf diseases were found to have a beneficial side effect in often giving a moderate reduction in *Fusarium* infection. However, it is suggested that this field exposure of *Fusarium* pathogens to fungicides may predispose towards future insensitivity problems. *In vitro* tests on the response of different *Fusarium* species to triadimenol fungicides showed a greater sensitivity in *F. nivale* and *F. dimerum* compared with other species which may be linked with their distinctive taxonomic grouping. The low incidence of *F. nivale* in the survey relative to that reported by earlier workers may be attributed in part to the more frequent application of fungicides to cereal crops in the field and the sensitivity of this fungus to the widely used triadimenol-containing formulations. A further factor accounting for the unexpectedly low incidence of *F. nivale* may have been the relatively mild winters and warm summers over the period of this survey which would be unfavourable to this low temperature fungus. From artificial inoculation of ears of different cereals with *Fusarium* species, *F. culmorum*, followed by *F. avenaceum* and *F. graminearum* were shown to depress grain yield significantly, *F. culmorum* having a major effect on grain size and the other two species causing a decrease in grain numbers. Earlier inoculations during the flowering period aggravated the effects of infection. The introduction of *T. roseum* 1 week before inoculation reduced these effects. The carry-over of ear inoculated *Fusarium* on seed was generally greater with the more pathogenic species, which also showed more deep-seated infection. However, the weak pathogen *F. sambucinum* also showed a high rate of carry-over and deeper penetration of seed tissues. Seed and soil inoculation tests confirmed that *F. culmorum* was the most pathogenic species, followed by *F. avenaceum* and *F. graminearum*. The addition of *T. roseum* to *Fusarium* inoculum adversely affected seed performance but other fungi, an isolate of *Penicillium* and of *Cladosporium*, reduced disease effects.

CONTENTS

SECTION 1
GENERAL INTRODUCTION

As with all crop plants, the cereals are subject to attack by a wide range of pathogens and pests which may cause considerable reductions in grain yield and quality. The extent of the problem will vary with location and year but the annual reduction in yield on a world basis has been estimated to be of the order of 12% (Jones & Clifford, 1983).

With respect to fungal diseases, several species of the genus *Fusarium* are recognized as pathogens of cereals. However, despite their frequent occurrence and widespread distribution they have received somewhat less attention, in terms of scientific study and practical concern, relative to that directed to, for example, the rusts, mildew, take-all and eyespots. These other diseases, caused by pathogens which themselves are conspicuous or give rise to well defined symptoms, are of undoubted importance. Nevertheless, *Fusarium* infection can also be damaging to the cereal crop, although its presence is often less clearly expressed. Moreover, *Fusarium* species may affect the crop throughout its life cycle, causing yield loss, reduced grain quality and, in some cases, a mycotoxin risk.

Fusarium species associated with cereals range from saprophytes to non-specialised, facultative parasites with a wide host range and exhibiting varying degrees of pathogenicity. The distribution of these various species and their relative importance appear to be environment-related, particularly with respect to temperature, rather than host-related although relatively few studies have been carried out on variation in host-pathogen interactions. The pathogenic *Fusarium* species of cereals are often found associated with other fungi such as *Alternaria*, *Cladosporium*, or *Trichothecium* yet little is known of the significance of any interactions between members of the *Fusarium* group associated with cereals and other microorganisms isolated from the cereal plant.

Finally, despite reports of the damage or potential damage to cereals linked with *Fusarium* species, according to Jones & Clifford (1983) *Fusarium* diseases of cereals have not ranked sufficiently high in the league of economic importance to warrant much attention in terms of control. Certainly, in comparison with cereal rusts, mildew, and eyespots, little attention has been paid to the response of *Fusarium* species to fungicide treatments in the field.

In view of the limited knowledge in several subject areas relating to this group of fungi the aim of the work reported here was to help to clarify the position of *Fusarium* species as pathogens of cereals and is in keeping with the opinion of several workers in recent years, that there is a need for some information on the occurrence and effects of *Fusarium* in cereal crops (Burgess, Wearing & Toussoun, 1975; Duben & Fehrmann, 1979; Wearing, 1979; Wilcoxson, Kommedahl, Ozmon & Windels, 1988).

In the present study attention is focused on barley (*Hordeum vulgare*), and wheat (*Triticum aestivum*) and to a lesser extent oats (*Avena sativa*) as cereal hosts of *Fusarium* species and five main aspects are considered as follows: (a) the distribution and seasonal pattern of development of *Fusarium* species and associated fungi on cereals in field plots in the east of Scotland, (b) the effect of fungicide treatments on the incidence of *Fusarium* infection and inter- and intra-specific variation in response of *Fusarium* to selected fungicides, (c) the effect of artificial ear inoculation of cereal plants with different *Fusarium* species, including those with a less well recognized pathogenic role, on grain development, (d) the effect of artificial ear inoculation as in (c) on seed and seedling performance, and (e) the effect of seed and soil inoculation with different *Fusarium* species on seedling growth and their interaction with different microorganisms, with particular reference to the status of *Trichothecium roseum* as an antagonistic or pathogenic organism.

SECTION 2

SURVEY STUDIES OF *FUSARIUM* SPECIES DISTRIBUTION IN CEREAL CROPS IN EAST SCOTLAND

2.1 INTRODUCTION

2.1.1 Taxonomy of *Fusarium* species

In any survey or observational studies on the genus *Fusarium* a worker is immediately faced with problems of identification and nomenclature. There must be few cases in the taxonomic literature where a single taxon has attracted more controversy than has the *Fusarium* group. *Fusarium* is a genus of the Deuteromycotina, an artificial sub-division relating to fungi lacking a known sexual phase. Where a sexual phase has been discovered *Fusarium* species have been assigned to various genera of the Ascomycotina but for many a sexual phase is unknown. Thus, the taxonomy within the *Fusarium* genus is based on artificial features, and often arbitrary, and this has led to some confusion and disagreement in the naming of species. Despite the long history of the genus, which was created by Link in 1809, it seems that a universally agreed system for this group has still not been written. At present there are basically two schools of thought on the speciation of the *Fusarium*. The one proposed by Wollenweber & Reinking (1935) and followed, with some modifications, by Raillo (1935; 1936; 1949; 1950), Gordon (1935; 1939; 1944; 1952; 1954a; 1954b; 1956a; 1956b; 1959; 1960a; 1960b; 1960c; 1961; 1965), Bilai (1952; 1955; 1970a; 1970b; 1977; 1978a; 1978b), Gerlach (1970; 1981), Gerlach & Nirenberg (1982):, Booth (1971; 1975; 1977), and Joffe (1974; 1986), and the other proposed by Snyder & Hansen (1940; 1941; 1945; 1954) followed by Messiaen & Cassini (1968, 1981), and Toussoun & Nelson (1975; 1976). In surveys in which vast quantities of plant material are examined and many *Fusarium* cultures have to be identified it would be easier to apply the system with 9 species proposed by Snyder & Hansen than the one with more than 65 species proposed by Wollenweber and Reinking, but by so doing, much information may be lost.

More recently Nelson, Toussoun & Marasas (1983) published a manual for identification of *Fusarium* species using a compilation of the different taxonomic systems. This seems to be closer to what a plant pathologist might need, although it still presents some difficulties in attempting to follow the keys or differentiating between certain species on the basis of the descriptions which are presented. In the present study the nomenclature of Booth (1971; 1977) and Nelson *et al.* (1983) is basically followed as summarized in Table 2.1, which lists the name of species as used in the text along with the teleomorph, where applicable, and both anamorphic and any teleomorphic synonyms. The species causing the greatest concern are *F. nivale* and *F. dimerum* which have been, as indicated in Table 2.1, recently assigned to other taxa. However the debate regarding these species is still continuing (Gams & Muller, 1980; Nirenberg, 1981; Nelson *et al.* 1983; Samuels & Hallett, 1983; Arx, 1984; Litschko & Burpee, 1987) and it was felt that until their position is more defined the original *Fusarium* nomenclature would be followed.

2.1.2 Distribution and economic importance of *Fusarium* species.

With regard to field fungi, *Fusarium* species are among the most common, having a world-wide distribution. These fungi have frequently been isolated from cultivated and non-cultivated soils of temperate, near-tropical and tropical regions, including soils ranging from Sahara desert sands to the Arctic permafrost. Commonly very adaptable, *Fusarium* species are capable of surviving many extreme environments due, in part, to their capacity for rapid morphological and physiological changes.

Many species within this genus are important plant pathogens, causing diseases of great importance on a wide range of crop plants. They include spoilage organisms

TABLE 2.1. Nomenclature of *Fusarium* species used in this study along with teleomorph name where known and synonyms.

ANAMORPH STATE Name used	 Synonym	TELEOMORPH STATE Name used	 Synonym
F. acuminatum[6]	*F. scirpi var acuminatum*[1] *F. equiseti var acuminatum*[7] *F. roseum* 'Acuminatum[3] *F. roseum var gibbosum*[5]	*Gibberella acuminata*[8]	*G. saubinetti dahliae*
F. avenaceum[1,6,7]	*F. roseum* 'Avenaceum[3] *F. roseum var avenaceum*[5]	*G. avenacea*[13]	Unknown
F. culmorum[1,6,7]	*F. roseum* 'Culmorum[3] *F. roseum var culmorum*[5]	Unknown	
F. dimerum[1,6,7]	*F. episphearia*[3,5] *M. dimerum*[15]	Unknown	
F. equiseti[6,7]	*F. equiseti*[1] *F. scirpi var compactum*[1] *F. scirpi var filiferum*[1] *F. roseum* 'Equiseti[3] *F. roseum* 'Gibbosum *F. roseum var gibbosum*[5]	*G. intricans*[8]	
F. graminearum[1,6]	*F.roseum* 'Graminearum[3] *F. roseum var graminearum*[5]	*G. zeae*[6,7]	*Sphaeria zeae*[10]
F. moniliforme[1,7]	*F. verticillioides*[6] *F. fujikuroi*[6] *F. moniliforme*[3,5]	*G. fujikuroi*[6,7]	*G. moniliformis*[11] *Lisea fujikuroi*[12]
F. nivale[1,6,7]	*F. nivale*[3,5] *Gerlachia nivalis*[14,15] *Microdochium nivale*[16]	*Monographella nivalis*[9]	*Calonectria nivalis* *Griphosphaeria nivalis* *Micronectriella nivalis* *Calonectria graminicola*
F. poae[1,6,7]	*F. tricinctum*[3,5]	Unknown	
F. oxysporum[6]	*F. oxysporum*[3,5] *F. redolens*[6] *F. oxysporum* *F. oxysporum*[7] *F. oxysporum var redolens*[7]	Unknown	
F. sambucinum[1,6,7]	*F.trichothecioides*[1,6] *F. bactridioides*[1,6] *F. sulphureum*[6] *F. sambucinum var trichothecioides*[7] *F. roseum* 'Sambucinum[3] *F. roseum var sambucinum*[5]	*G. pullicaris*	*Sphaeria pullicaries*[17]
F. semitectum[1,6,7]	*F. roseum* 'Semitectum[3] *F. roseum var arthrosporioides*[5]	*Unknown*	
F. sulphureum	*F. sambucinum*	*G. cyanogena*	*Sphaeria cyanogena* *Gibberella saubinetti*
F. solani[6,7]	*F. javanicum*[6,7] *F. coeruleum*[6] *F. solani*[3,5] *F. eumartii*[6] *F. illudens*[6] *F. ventricosum*[6] *F. solani var coeruleum* *F. timidum*[2] *F. solani var coeruleum*[7] *F. solani var ventricosum*[7]	*Nectria haematococca*	*Nectria diversispora*[10]
F. sporotrichioides[6,7]	*F. tricinctum*[3,5]	Unknown	
F. tricinctum	*F. sporotrichioides var tricinctum*[7] *F. tricinctum*[3,5]	*G. tricincta*	

Anamorph and teleomorph names based on reference to Booth (1971; 1981)* or Nelson *et al.* (1983)* or both. Other names based on references as follows:

1. Wollenweber & Reinking (1935)
2. Booth (1971; 1981)
3. Snyder & Hansen (1940; 1941; 1945; 1954)
4. Nelson, Toussoun & Marasas (1983)
5. Messiaen & Cassini (1968; 1981)
6. Gerlach (1981)
7. Joffe (1968; 1982)
8. Wollenweber & Reinking (1935)
9. Muller (1977)
10. Petch (1921)
11. Sawada (1912)
12. Wineland (1924)
13. Cook (1967)
14. Arx (1984)
15. Gams & Muller (1980)
16. Samuel & Hallett (1983)
17. Fries (1849)

of storage products and often produce toxins which contaminate human and animal food.

Fusarium species are world-wide in geographical distribution and equally wide-ranging in the variety of plant species they attack. Few, if any economically important crops are safe from this ubiquitous genus. However, they are limited in the number of ways in which they cause disease. These fungi may be grouped into two categories, the vascular wilt *Fusaria* and the cortical rot *Fusaria*, on the basis of the disease syndromes (Pennypacker, 1981). Most of *Fusarium* wilt diseases are caused by *formae speciales* of *F. oxysporum* and are primarily soil-borne. The remaining *Fusaria* attack the cortex, storage tissue or seed of the host and may be soil-, air- or seed-borne.

Some species of *Fusarium* are known to be extremely variable in cultural and morphological characteristics and this variability may also be observed in pathogenicity studies of different species and isolates. Many species of this genus are able to produce metabolites of biological significance to other organisms, including mycotoxins which have been extensively studied because of their role in animal diseases and several *Fusarium* toxins have been identified in this light, including zearalenone which causes the oestrogenic syndrome in pigs. The role of *Fusarium* toxins in plant pathogenesis is at present little understood although their phytotoxicity has in some cases been confirmed, especially amongst the vascular wilt *Fusaria* (Gaumann, 1957; 1958).

Fusarium species associated with crop cereals cause serious yield losses in staple food crops throughout the world. Economically, the most important are *F. avenaceum*, *F. culmorum*, *F. graminearum*, *F. moniliforme* and *F. nivale*. These species are important in pre- and post-emergence seedling blight, root and foot rots and head blight or scab of cereals.

In the case of seedling establishment, Malalasekera, Sanderson & Colhoun (1973) when studying the penetration and invasion of wheat seedlings by *F. culmorum* and *F. nivale*, found these fungi in the coleorrhiza and parts of the roots adjacent to it. When these two fungi penetrate the coleoptile, intercellular prosenchymatous hyphal mats are soon formed, but *F. culmorum* forms an intracellular mycelium more frequently than *F. nivale*. Earlier, Atanasoff (1920) regarded the coleorrhiza and coleoptile as the bases from which an attack by *F. graminearum* spread in wheat seedlings.

Cook (1968) suggested that there are two routes by which *Fusarium* can cause crown and foot rot during the vegetative growth stage. The attack may start above ground from conidia, ascospores or mycelia, in which case the fungus must penetrate the successive layers of leaf sheaths to reach the culm. Generally this happens where the inoculum is trapped in the leaf whorls, where adequate moisture and humidity are available for fungal growth on aerial parts and where pollen collects and is used as a food source by *Fusarium*. Once in the culm, the infection may progress upwards one or two internodes, or downwards into the crown. The second route may be from underground. The soil-borne, cortical-rotting species of *Fusarium* generally infect the roots or hypocotyl of the host by penetrating indirectly via the stem base stomata or wounds (Pennypacker, 1981), or directly through the root tip, or meristematic region, of the roots (Malan, 1969). *F. culmorum* and *F. graminearum* have been shown to cause a crown and basal culm rot that starts with root infection from soil- or seed-borne inoculum and these extend one to three internodes up the culm. With this route leaf sheaths commonly show no evidence of disease, and must be peeled away to reveal the brown foot rot. Both routes may produce plant blight (white heads) just after heading. Although any of the pathogenic *Fusarium* species are apparently capable of causing crown and basal stem rot by either of the two routes described above , *F. culmorum* and *F. graminearum* (Francis & Burgess, 1977) are the most important pathogens where below-ground infections are concerned. The majority of the cortical *Fusarium* species become intracellular in the cortical cells during the later stage of pathogenesis. Whether root and crown infections remain in the chronic (common root rot) stage, or develop into the more acute (crown and brown foot rot) stages seems to depend on the occurrence of very low plant water potentials (Papendick & Cook, 1974). Root infections may weaken the anchorage of plants in the soil and, thus, cause lodging. Infections of leaves and upper stems by *Fusarium* species have been reported by some workers but it seems that they do not occur under normal circumstances, for in those cases the presence of other pathogens, e.g. *Erysiphe graminis*, was required (Mesterhazy & Rowaished, 1977).

Ears are extremely susceptible to attack from flowering onwards, infection of florets leading to either sterility of the inflorescence or discoloured and shrivelled or sterile grain. Early studies have shown that *F. graminearum* colonizes all parts of the wheat kernel both intercellularly and intracellularly and that it penetrates cells intracellularly via apressoria-like structures (Adams, 1921; Pugh, Johann & Dickson, 1933). Bennett (1928) reported that *F. culmorum* and *F. avenaceum* were seed-borne; later Malalasekera & Colhoun (1969) found that *F. culmorum* rarely, if ever, penetrates as far as the embryo but that hyphae were present on the outer and inner surfaces of seed coat and also formed a prosenchymatous mat beneath the seed coat. Ear infections by *F. graminearum* and *F. culmorum* appear to be facilitated by the early colonization of other species of *Fusarium* such as *F. poae* and *F. avenaceum* (Sturz & Johnston, 1983). However, most of the workers have concluded that wheat heads are most susceptible to infection by *Fusarium* species at the flowering stage not because of the pre-colonization of other fungi but due to chemical compounds, notably choline and betaine, produced by the plants at the anthesis stage (Strange, Majer & Smith, 1972; 1974). This statement is supported by the fact that wheat spikes were not receptive to the pathogens prior to anthesis, but were receptive in the period from flowering to the soft dough stages, after which receptivity declined rapidly (Mesterhazy & Rowaished, 1977). Further reference to ear and grain infection is giving in Section 4.

In many parts of the world, including the People's Republic of China (PRC), scab caused by *F. graminearum* is the most important of the *Fusarium* diseases of cereals (Kelman & Cook, 1977). Tusa, Munteanu, Capett, Pirvu, Bunescu, Sin, Nicolae, Tianu, Caea, Romascanu, & Stoica (1985) found that ear blight attacked wheat at all stages of development, causing losses of yield up to 40% in the individual regions of Romania and up to 70% in some fields. A similar case is presented in the Toluca Valley in Mexico where head blight of wheat causes losses that range from 17 to 70% depending on the weather conditions and sown varieties (Ireta, 1986).

2.1.3 Isolation media for *Fusarium* species

In sampling soil or parts of plants for counts of *Fusarium* species, the method must reveal the general distribution of the fungi units within a field and in the zones immediately around the underground parts of the plants, since some of these fungi grow only a short distance through field soil. A further concern is the selective isolation of the *Fusarium* species from a large and complex population of soil microorganisms. During the last two decades some researchers have been trying to find a good selective isolation medium for some of the *Fusarium* species (Nash & Snyder, 1962; Papavizas, 1967; Tsao, 1970; Tickle, 1974; Jeffries, 1978; Andrews & Pitt, 1986). The recovery of these important pathogens is significantly influenced by the isolation technique as well as by variable site factors or sampling year. Thus, it has been suggested that the use of only one isolation technique may fail to provide the optimum conditions for recovery from soil or parts of the plants of a maximum number of species of *Fusarium* or of an individual species.

The number of isolation media recommended for *Fusarium* species is large (Parmeter & Hood, 1961; Nash & Snyder, 1962, Stover, 1962; Wensley & McKeen, 1962; Booth, 1971). However, only two, PPA (PCNB-peptone-agar) and DCPA (dichloran-chloramphenicol-peptone-agar), have been consistently successful. PPA was first used by Nash & Snyder (1962) to isolate *F. solani* f.sp. *phaseoli* in field soils with common bean (*Phaseolus vulgaris*). They found this medium to be one of the simplest and most satisfactory for making dilution plates for *F. solani* f. sp. *phaseoli*. DCPA has more recently been recommended by Andrews & Pitt (1986) as a selective medium for isolation of *Fusarium* species and Dematiaceous Hyphomycetes from cereals. The medium was found to select against species of *Aspergillus*, *Penicillium*, *Cladosporium*, and mucoraceous fungi. It was observed that *Fusarium* species and Dematiaceous Hyphomycetes produced well-formed colonies with good conidial production on DCPA which permitted rapid identification of such isolates on this medium.

McMullen & Stack (1983), obtained good results when using root isolation techniques including Martin's rose bengal medium (MRB) (Martin, 1950), which suggested that this medium would enhance recovery of *Fusarium* species from roots. McMullen & Stack (1983) observed that MRB medium showed less inhibitory effects than PPA or Komada (Komada, 1975) media to the *Fusaria* growing slowly from the inner tissues of the surface-disinfected root pieces. They also found more species more frequently isolated by use of debris technique and MRB medium. These workers plated sieved debris following the procedure described by Tio, Burgess, Nelson & Toussoun (1977). One hundred and twenty pieces of debris ranging in size from 0.3 mm to 1 cm in length and 0.3-5 mm in diameter were cultured per composite sample.

In 1981 Nirenberg, found that by using an agar with low nutrient content (SNA) and keeping the inoculated Petri dishes under continuous black light, usually time-consuming procedures could be avoided. His medium apparently stimulated large and uniform quantities of conidia in the aerial mycelium. They found SNA to be as good as CLA (carnation leaf agar) recommended by Fisher, Toussoun & Burgess (1981). However, in our preliminary studies the medium seemed to be unsuitable for isolation studies. The medium allowed growth of other fast growing fungi such as *Mucor*, *Rhizopus*, *Trichoderma* and bacteria that inhibited *Fusarium* growth. Similar results have been obtained by Miles (1989) (Personal communication).

The experimental work in this section was concerned with an assessment of the incidence of *Fusarium* and associated fungal species on cereal plants sampled from fungicide trial plots laid out by the East of Scotland College of Agriculture

(ESCA) in the east of Scotland in 2 years, 1987 and 1988, using different isolation media. General aspects relating to incidence are considered here and the effects of fungicide treatments are considered in the next section.

2.2 MATERIALS AND METHODS.

2.2.1 Isolation media

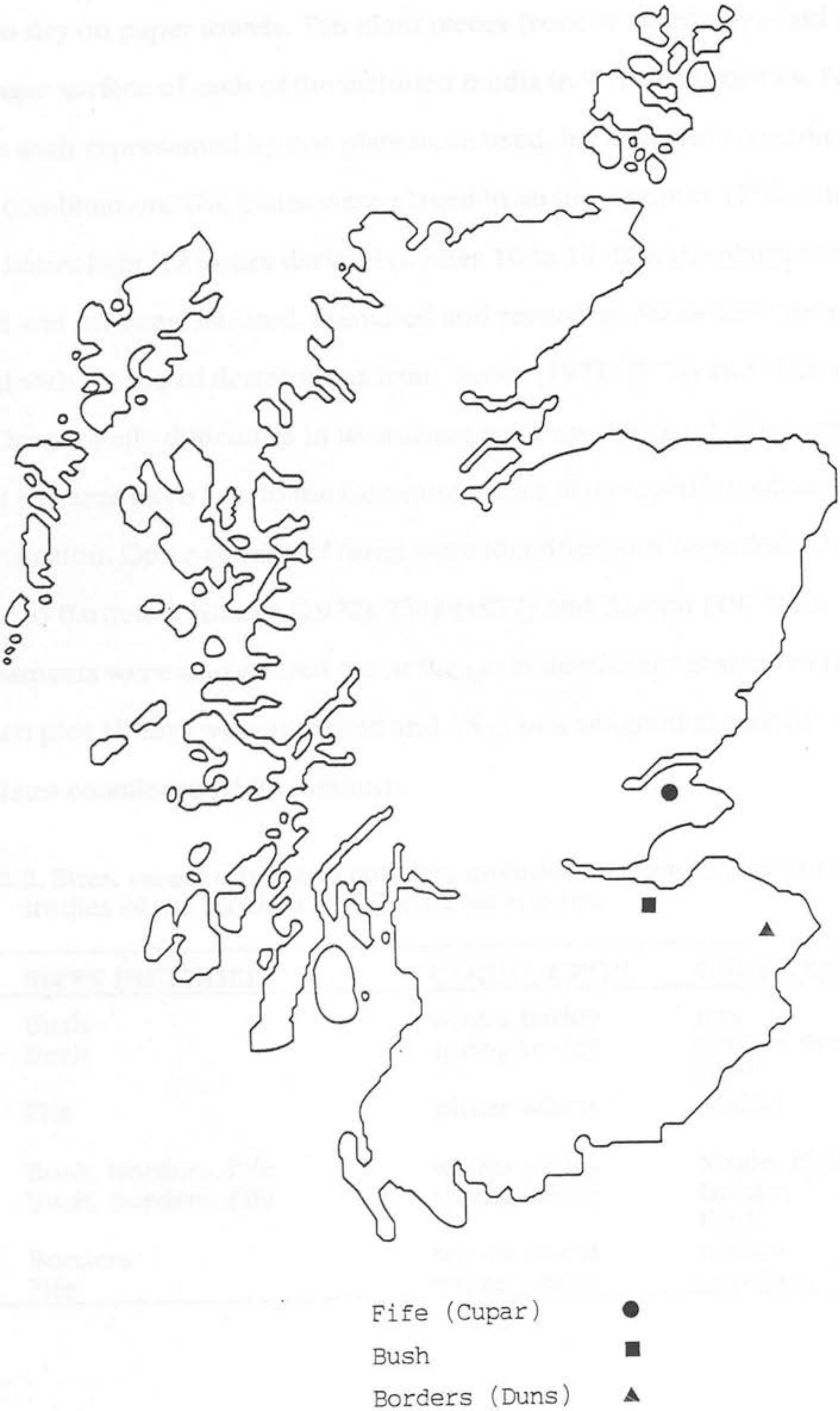
The media used in this study for the isolation of *Fusarium* species and other fungi occurring on roots, stems and ears of barley and wheat were PPA, PDA and MRB in 1987. In the following year DCPA was also used but PDA and MRB were excluded. Formulations and preparation procedures are given in Appendix I.

2.2.2 Sites and sampling procedure.

In this work fungicide trials with winter barley, spring barley and winter wheat were included to assess the incidence of *Fusarium* species and other fungi occurring on roots, stems and ears in east Scotland (Figure 2.1). All the experiments consisted of 0.0036 ha plots of each treatment marked out in a randomized block design replicated four times, except in 1988 for winter barley when three replicates of two cultivars were used. In 1987 the trial with winter barley consisted of one cultivar only. Fertilizer, herbicide and other agronomic treatments were the same in all plots. Sites and cultivars are shown in Table 2.2. With regard to the dates of sampling, they are listed in the different tables of results and the various fungicide treatments applied are indicated in Section 3. An illustration of a trial site is given in Plate 2.1.

Ten plants with at least two tillers each were taken at random from each of the plots in the different sites at each sampling date. Plants from each plot were washed with tap water in order to free the roots of soil, and then cut 5 cm above

Figure **2.1** Location of sites of fungicide field trials.



the crown. Twenty pieces of stem about 1 cm in length and 20 pieces of root of approximately 1 cm, both near the crown, were cut. Root and stem pieces were surface sterilized for 5 minutes in 1.5% and 10% ethyl alcohol respectively, and allowed to dry on paper towels. Ten plant pieces (root or stem) were laid upon the firm agar surface of each of the included media in 9-cm Petri dishes. Four replicates each represented by one plate were used, for each field treatment and medium combination. The plates were placed in an incubator at 17^{o}C with black light (12 hours light/12 hours darkness). After 10 to 14 days the plates were inspected and the fungi isolated, identified and recorded. *Fusarium* species were identified with the aid of descriptions from Booth (1971; 1977) and Nelson *et al.* (1983). Occasionally difficulties in identifying were encountered. When this occurred cultures were sent to the Commonwealth Mycological Institute at Kew for confirmation. Other species of fungi were identified and recorded following reference to Barnett & Hunter (1972), Ellis (1977) and Barron (1977). In 1988, ear assessments were also carried out at the grain development stage of growth. From each plot 10 ears were threshed and 15 grains assigned at random to each of two plates containing DCPA medium.

TABLE 2.2. Sites, cereal crops and cultivars included in the two-year survey studies of the incidence of *Fusarium* species.

YEAR	SITES INCLUDED	CEREAL CROP	CULTIVARS
1987	Bush	winter barley	Igri
1987	Bush	spring barley	Golden Promise, Golf
1987	Fife	winter wheat	Avalon
1988	Bush, Borders, Fife	winter barley	Magie, Plaisant
1988	Bush, Borders, Fife	spring barley	Golden Promise, Golf
1988	Borders	winter wheat	Avalon
1988	Fife	winter wheat	Longbow

PLATE 2.1. View of winter wheat field trial at Fife site, 1987.

In considering the results, analyses of variance were carried out for the most prevalent *Fusarium* species, the remaining species being presented simply as their average percentage occurrence because of their infrequent or sporadic recovery at a low level. Where analyses of variance were carried out both the original percentages and transformed data (arc sin) were analysed but they showed no divergences in the assessment of treatment effects and only the original percentages are presented. Fungicide treatment details and results, as already stated, are given consideration in Section 3.

2.3 RESULTS

The results of the survey of fungi present on cereal plants and the analyses of the data, where appropriate, are summarised in Tables 2.3 to 2.11 and in Appendices II to V. In this section the effects on the recorded frequency of species of isolation medium, site, host crop, cultivar, plant part and time of sampling, all averaged for the various fungicide treatments, are considered and the results are presented under the following headings:

1. The effect of isolation medium on the recovery frequency of *Fusarium* species;

2. Variation in the frequency of *Fusarium* species and other fungi between different sites and host crops;

3. The incidence of *Fusarium* species and other fungi in relation to time of sampling and plant part for different cereal crops.
   (a) Winter barley
   (b) Spring barley
   (c) Winter wheat

2.3.1 The effect of isolation medium on the recovery of *Fusarium* species.

The main purpose of the survey was to assess the incidence of *Fusarium* organisms in cereal crops and the results for the effects of isolation medium on the recovery frequency of the more prevalent species are given in Tables 2.3 to 2.5. Of the three media tested during 1987, MRB tended to give low numbers of

TABLE 2.3. Percentage frequency of isolation from winter barley roots (R) and stems (S) of different species within the *Fusarium* group in relation to isolation media.

FUSARIUM SPECIES	PLANT PART	BUSH 1987 PPA	MRB	SED±	BUSH 1988 PPA	DCPA	SED±	FIFE 1988 PPA	DCPA	SED±	BORDERS 1988 PPA	DCPA	SED±
F. avenaceum	S	2	<1	1.6	-	-	-	-	-	-	-	-	-
	R	<1	2	0.9	-	-	-	-	-	-	-	-	-
F. culmorum	S	30	15	6.4	16	16	3.0	26	16	2.4	19	15	2.7
	R	19	10	2.8	16	15	3.3	10	8	1.8	7	9	2.7
F. dimerum	S	64	1	2.9	15	10	3.2	24	22	2.7	26	17	3.2
	R	82	0	4.1	40	32	4.0	58	55	3.2	49	38	4.5
F. nivale	S	-	-	-	-	-	-	17	11	2.8	-	-	-
	R	-	-	-	-	-	-	4	3	1.3	-	-	-
F. poae	S	0	<1	0.2	-	-	-	-	-	-	-	-	-
	R	0	<1	0.4	-	-	-	-	-	-	-	-	-
F. sambucinum	S	-	-	-	20	19	2.5	-	-	-	22	12	2.6
	R	-	-	-	5	6	2.2	-	-	-	7	9	2.1

-Not present or trace only

Fusarium colonies from roots and stem bases, while allowing extensive growth of associated microorganisms: for example, no appreciable recovery of *F. dimerum* could be obtained from stems and roots on this medium, 1 and 0% compared with 64 and 82% on PPA (Table 2.3). In general the other three media, viz. PDA, PPA and DCPA showed with a few exceptions more or less similar levels of the most prevalent *Fusarium* species. Where significant differences did occur they were generally not of great magnitude. It was observed, however, that PDA allowed a more vigorous growth of saprophytic fungi and this medium tended to give a lower frequency of *Fusarium* compared with PPA (Table 2.4 & 2.5). Although not statistically significant in most of the cases, PPA tended to be slightly superior to DCPA in the rate of isolation of *Fusarium*.

2.3.2 Variation in the frequency on roots, stems and ears of *Fusarium* species and other fungi between different sites and host crops

The general distribution of fungi which were more prevalent, ie with an average isolation frequency of at least 10% at one or more of the sites, is summarised in Tables 2.6 to 2.8 to illustrate in broad terms the occurrence of the main species which were found in relation to site and host crop on roots stems and ears respectively.

Of the *Fusarium* species, *F. culmorum* and *F. dimerum* predominated on roots throughout this study, the isolation rates ranging from 35 to 60 for *F. dimerum* and from 9 to 36 % for *F. culmorum* (Table 2.6). Levels varied to some extent at the different sites but there was no evidence that either species exhibited a marked host preference. Of the remaining species, *F. avenaceum, F. nivale,* and *F. poae* rarely if ever showed a frequency above 4% while *F. sambucinum* was usually slightly more prevalent with a percentage ranging from 0 to 13. *Cylindrocarpon*

TABLE 2.4. Percentage frequency of isolation from spring barley roots (R) and stems (S) of different species within the *Fusarium* group in relation to isolation media.

FUSARIUM SPECIES	PLANT PART	BUSH 1987 PPA	BUSH 1987 PDA	BUSH 1987 SED±	BUSH 1988 PPA	BUSH 1988 DCPA	BUSH 1988 SED±	BORDERS 1988 PPA	BORDERS 1988 DCPA	BORDERS 1988 SED±	FIFE 1988 PPA	FIFE 1988 DCPA	FIFE 1988 SED+
F. avenaceum	S	3	5	1.0	-	-	-	-	-	-	-	-	-
	R	2	3	0.6	-	-	-	-	-	-	-	-	-
F. culmorum	S	44	30	1.6	51	48	1.4	42	33	2.8	21	21	2.5
	R	17	13	2.2	31	31	1.8	9	8	1.9	12	12	2.1
F. dimerum	S	65	49	2.4	9	6	1.2	21	16	2.6	14	13	2.4
	R	74	58	2.8	23	25	2.4	35	38	2.9	36	29	3.3
F. nivale	S	-	-	-	-	-	-	3	1	0.9	7	6	1.4
	R	-	-	-	-	-	-	4	2	1.5	3	2	1.5
F. poae	S	2	3	0.9	-	-	-	-	-	-	-	-	-
	R	3	5	1.1	-	-	-	-	-	-	-	-	-
F. sambucinum	S	-	-	-	5	4	0.9	2	1	0.4	8	4	2.2
	R	-	-	-	3	3	0.7	1	1	0.5	<1	2	0.9

-Not present or trace only

TABLE 2.5. Percentage frequency of isolation from wheat roots (R) and stems (S) of different species within the *Fusarium* group in relation to isolation media.

FUSARIUM SPECIES	PLANT PART	FIFE 1987 PPA	FIFE 1987 PDA	FIFE 1987 SED±	FIFE 1988 PPA	FIFE 1988 DCPA	FIFE 1988 SED±	BORDERS 1988 PPA	BORDERS 1988 DCPA	BORDERS 1988 SED±
F. avenaceum	S	7	6	0.9	12	6	2.4	-	-	-
	R	1	1	0.4	3	2	1.5	-	-	-
F. culmorum	S	37	36	2.4	27	20	2.4	44	34	2.0
	R	14	14	1.8	13	9	2.1	14	13	2.3
F. dimerum	S	31	26	3.2	6	4	1.6	2	4	1.3
	R	51	38	3.5	40	20	3.1	36	24	2.8
F. nivale	S	-	-	-	1	1	0.4	4	7	1.3
	R	-	-	-	2	2	0.6	7	7	1.2
F. poae	S	7	7	1.2	-	-	-	-	-	-
	R	19	18	2.1	-	-	-	-	-	-
F. sambucinum	S	-	-	-	13	14	1.8	12	8	2.1
	R	-	-	-	8	8	1.9	2	2	0.8

-Not present or trace only

TABLE 2.6. Percentage frequency of isolation from roots of fungi for different sites, years and host crops (averaged for dates of sampling, various fungicide and cultivar treatments and isolation media).

FUNGAL SPECIES	WINTER BARLEY				SPRING BARLEY				WINTER WHEAT		
	BUSH* 1987	BUSH 1988	BORDERS 1988	FIFE 1988	BUSH 1987	BUSH 1988	BORDERS 1988	FIFE 1988	FIFE* 1987	FIFE* 1988	BORDERS* 1988
F. avenaceum	1	2	1	2	2	1	2	2	4	2	2
F. culmorum	14	18	9	9	11	36	10	14	12	17	19
F. dimerum	41	45	47	60	53	35	53	44	37	45	39
F. nivale	0	0	0	3	0	1	4	2	0	4	8
F. poae	0	3	0	1	4	1	0	0	16	0	0
F. sambucinum	0	7	8	3	2	3	3	2	1	13	8
Alternaria	<1	0	0	1	3	0	<1	0	3	1	1
Cladosporium	0	3	3	1	2	3	1	2	0	2	1
Cylindrocarpon	30	12	21	5	5	12	10	7	24	7	13
Mucor	1	1	2	2	2	4	2	2	0	2	3
Penicillium	7	7	4	5	3	26	9	23	<1	4	13
Trichothecium	0	2	1	0	0	0	1	0	0	0	0

* Only one cultivar used

and *Penicillium* were the most prevalent of other fungi to be isolated: *Cylindrocarpon* occurred in an average of from 5 to 30% of the samples, while *Penicillium* was more erratic in its incidence which ranged from < 1 to 26%. The highest incidences of *Cylindrocarpon* occurred at the winter barley and winter wheat sites while for *Penicillium* at the spring barley sites. Other fungi included *Alternaria*, *Cladosporium*, *Mucor* and *Trichothecium (T. roseum)* which occurred only at low levels, never more than 4%.

On stems (Table 2.7), *F. culmorum* and *F. dimerum* were again the most prevalent species. In contrast to roots where *F. dimerum* was more frequently isolated than was *F. culmorum*, on stems *F. culmorum* preponderated ranging from 18 to 55% in comparison with 4 to 30% for *F. dimerum*. Variation between sites occurred, but with no clear evidence of a host crop preference for either species. The other *Fusarium* species, *F. avenaceum*, *F. poae*, *F. nivale* and *F. sambucinum* were recorded at generally a low or moderate level, *F. sambucinum* being the most prevalent of this group and *F. poae* the least. Of the other fungi *Mucor* and *Penicillium* were isolated frequently from stems and *Alternaria*, *Cladosporium*, *Cylindrocarpon* and *Trichothecium* were recorded in smaller amounts.

With regard to ears (Table 2.8), *F. culmorum* was again one of the more prevalent colonizers, with a percentage frequency ranging from 2 to 27%, but *F. dimerum* was completely absent. *F. culmorum* was a major component of the *Fusarium* mycoflora on ears of winter barley at Fife, at all spring barley sites and on ears of winter wheat at the Borders site. *F. avenaceum* was prevalent on ears of winter barley at Bush, and *F. nivale* was a prevalent species of *Fusarium* at Fife in all three cereal crops. *F. poae* was only occasionally found and *F. sambucinum*

TABLE 2.7. Percentage frequency of isolation from stems of fungi for different sites, years and host crops (averaged for dates of sampling, various fungicide and cultivar treatments and isolation media).

FUNGAL SPECIES	WINTER BARLEY				SPRING BARLEY				WINTER WHEAT		
	BUSH* 1987	BUSH 1988	BORDERS 1988	FIFE 1988	BUSH 1987	BUSH 1988	BORDERS 1988	FIFE 1988	FIFE* 1987	FIFE* 1988	BORDERS* 1988
F. avenaceum	1	1	2	0	3	2	2	2	4	10	3
F. culmorum	34	24	18	25	44	55	46	23	34	26	42
F. dimerum	23	19	25	25	27	12	25	14	30	6	4
F. nivale	0	2	0	12	0	1	2	7	0	1	3
F. poae	0	1	0	1	2	1	0	0	7	0	0
F. sambucinum	0	12	17	6	3	5	2	6	1	15	3
Alternaria	6	<1	0	<1	3	0	<1	0	7	1	1
Cladosporium	0	6	6	2	2	2	<1	3	0	2	4
Cylindrocarpon	18	3	7	3	5	4	7	2	4	2	2
Mucor	3	20	12	16	2	8	5	21	0	30	18
Penicillium	10	3	3	4	1	12	5	17	1	7	10
Trichothecium	0	2	1	0	0	<1	5	0	0	0	0

*Only one cultivar used

TABLE 2.8. Percentage frequency of isolation from ears of fungi for different sites, years and host crops (averaged for dates of sampling, various fungicide and cultivar treatments and isolation media).

FUNGAL	WINTER BARLEY			SPRING BARLEY			WINTER WHEAT	
SPECIES	BUSH 1988	BORDERS 1988	FIFE 1988	BUSH 1988	BORDERS 1988	FIFE 1988	BORDERS* 1988	FIFE* 1988
F. avenaceum	18	<1	<1	4	2	1	3	4
F. culmorum	2	7	20	27	12	17	19	2
F. dimerum	0	0	0	0	0	0	0	0
F. nivale	1	1	20	2	2	26	6	12
F. poae	1	0	1	1	0	0	0	0
F. sambucinum	<1	<1	0	1	7	0	6	0
Alternaria	6	7	9	4	5	0	6	7
Cladosporium	47	35	32	10	15	21	34	45
Epicoccum	6	6	8	12	37	23	33	27
Penicillium	3	13	<1	0	0	0	1	0
Septoria	0	30	5	0	0	0	0	0
Trichothecium	0	0	0	33	10	5	0	0

*Only one cultivar used

occurred at the Bush and Borders sites, but only at a low to moderate level. Of the other fungi *Cladosporium* and *Epicoccum* were the most prevalent on ears throughout this study. *Alternaria* and *Penicillium* were found at some sites at moderate levels. *T. roseum* was found at all three spring barley sites and *Septoria* in winter barley at two of the three sites.

2.3.3 The incidence of *Fusarium* species and other fungi in relation to time of sampling and plant part for different cereal crops.

(a) Winter barley

In the trials with winter barley one cultivar, Igri, was used in 1987. In 1988, however, two cultivars Magie and Plaisant were assessed in two separate but adjacent trials. These results for cultivars were not directly comparable statistically but no major and consistent differences seemed to occur in the populations of fungi in the two cultivars. Thus, in considering the two most prevalent *Fusarium* species, *F. culmorum* and *F. dimerum*, it may be seen from Figure 2.2 that the general levels of occurrence on the two cultivars were usually of similar magnitudes in comparable instances and any differences tended to be inconsistent.

The more frequently occurring *Fusarium* species recorded in the survey of winter barley are listed in Table 2.9. Species which were less frequent (incidence generally less than 1%) are listed in Table 2.10. A major feature of the results is the prevalence of *F. culmorum* and *F. dimerum* on roots and stems. *F. culmorum* was more frequently isolated from stems than from roots and usually increased with later sampling. *F. dimerum*, on the other hand, showed a higher incidence on roots than on stems and, while tending to increase on roots with time, declined

FIGURE 2.2 Percentage frequency of isolation of *F. culmorum* and *F. dimerum* from stems and roots of winter barley cvs. Magie and Plaisant at different dates of sampling (averaged for isolation media)–1988.

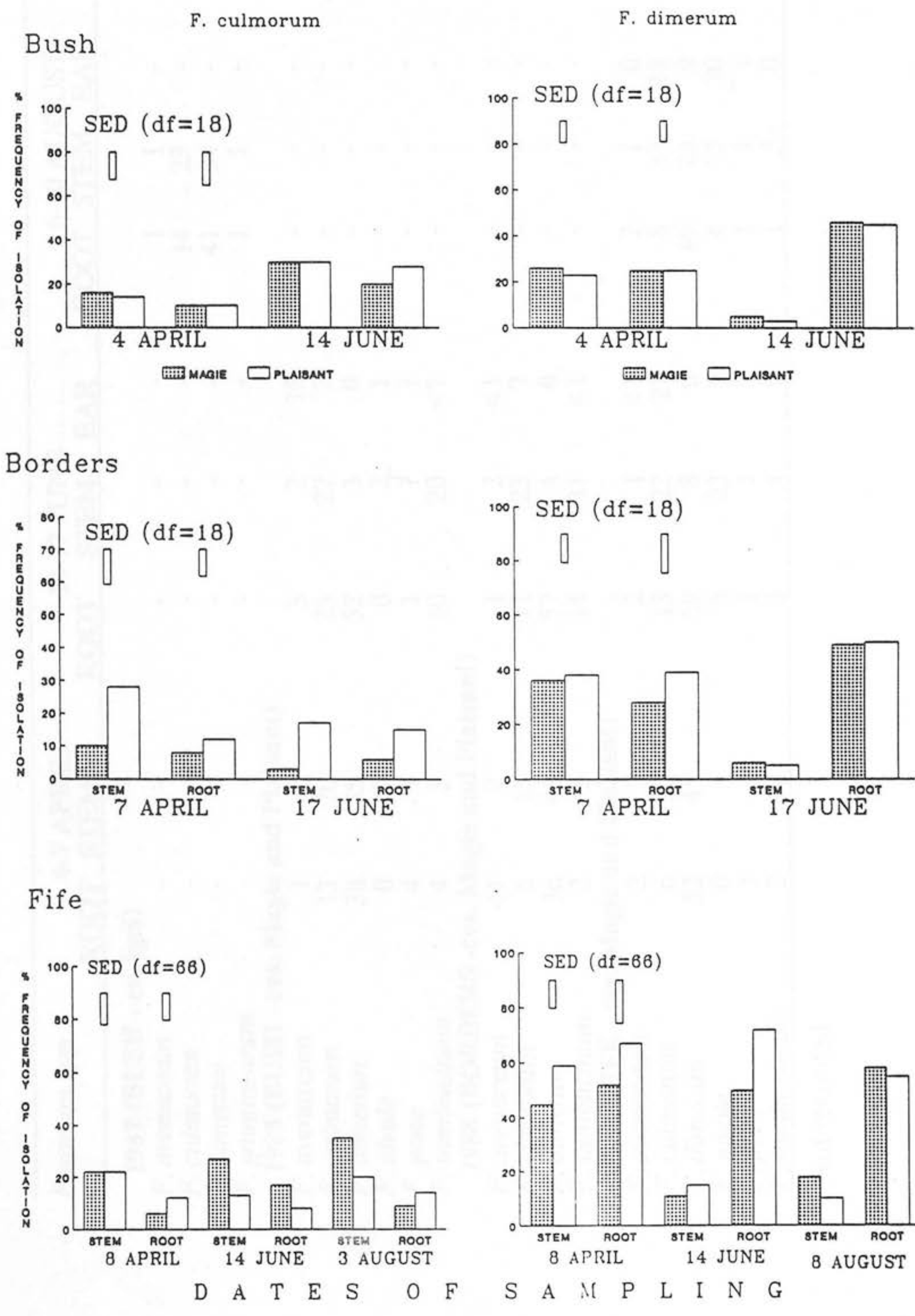


TABLE 2.9. Percentage frequency of isolation of different species of the *Fusarium* group from winter barley roots, stems and ears from four sites, 1987-1988 sampled at different growth stages (average for different cultivars, fungicide treatments and for isolation media).

Fusarium spp.	4-7 APRIL		14-17 JUNE			6-10 AUGUST		
	ROOT	STEM	ROOT	STEM	EAR	ROOT	STEM	EAR
1987 (BUSH - cv. Igri)								
F. avenaceum	-	-	-	-	-	1	1	-
F. culmorum	-	-	-	-	-	14	23	-
F. dimerum	-	-	-	-	-	41	34	-
F. graminearum	-	-	-	-	-	1	1	-
1988 (BUSH - cvs. Magie and Plaisant)								
F. avenaceum	1	0	3	2	18	-	-	-
F. culmorum	13	20	23	27	2	-	-	-
F. dimerum	38	35	52	3	0	-	-	-
F. nivale	0	2	0	2	1	-	-	-
F. poae	4	1	1	1	1	-	-	-
F. sambucinum	4	3	10	20	<1	-	-	-
1988 (BORDERS -cvs. Magie and Plaisant)								
F. avenaceum	<1	2	1	2	<1	-	-	-
F. culmorum	6	13	11	23	7	-	-	-
F. dimerum	36	46	57	4	0	-	-	-
F. sambucinum	2	3	14	31	<1	-	-	-
1988 (FIFE - cvs. Magie and Plaisant)								
F. avenaceum	2	3	2	1	<1	2	1	0
F. culmorum	6	20	13	22	21	8	33	18
F. dimerum	52	45	59	8	0	69	23	0
F. nivale	0	1	5	23	9	4	12	30
F. poae	1	1	1	1	1	1	1	1
F. sambucinum	2	10	3	4	0	1	3	0

-Not recorded

TABLE 2.10. Infrequent *Fusarium* species and other fungi isolated from roots, stems and ears of winter barley planted at Bush in 1987 (1), and Bush (2), the Borders (3) and Fife (4) in 1988.

FUSARIUM	ROOT				STEM				EAR		
SPECIES	1	2	3	4	1	2	3	4	2	3	4
F. acuminatum	-	+	-	-	-	-	-	-	+	-	+
F. equiseti	+	+	-	+	+	+	-	-	-	+	+
F. graminearum	+	+	+	-	+	+	+	-	-	+	-
F. moniliforme	+	-	-	-	+	-	+	+	+	-	+
F. poae	+	+	+	+	+	+	+	+	+	+	+
F. oxysporum	-	+	+	+	-	-	-	-	-	-	-
F. semitectum	-	+	-	-	-	+	+	+	-	-	+
F. sulphureum	-	+	-	-	-	+	-	-	-	-	-
F. solani	-	-	-	+	-	-	-	-	-	-	-
F. sporotrichioides	-	-	-	-	-	-	-	-	+	-	-
F. tricinctum	-	-	+	-	-	-	+	-	-	-	+
OTHER FUNGI											
Botrytis	-	-	-	-	-	-	-	+	+	+	+
Beige fungus	-	-	-	-	-	-	-	-	+	-	-
Paecilomyces	-	+	+	+	-	+	+	+	-	-	-
Rhizoctonia	+	+	+	+	+	+	+	+	-	-	-
Septoria	-	+	-	-	-	+	-	-	+	-	-
Ulocladium	-	-	-	-	-	-	-	-	-	+	+
White fungus	-	-	-	-	-	-	-	-	-	+	+

-Not present
+Present

on older stems. Of the other species of *Fusarium*, *F. sambucinum* was often isolated from roots and stems of plants planted at Bush and the Borders sites in 1988 at the second date of sampling and *F. nivale* was prevalent on stems from Fife sampled during the second date but later declined. Only *F. culmorum*, *F. avenaceum* and *F. nivale* were ever abundant on ears. *F. avenaceum* predominated at Bush but was not recorded or seen only in trace amounts at other centres. *F. culmorum* was frequent on the ears at the Borders and Fife sites together with *F. nivale* at the last centre. Occasionally *F. poae* and *F. sambucinum* were isolated from ears. The isolation of other species of *Fusarium* (Table 2.10) was sporadic with *F. oxysporum* confined to the roots and the rest usually occurring more generally over the plants.

In addition to *Fusarium* many other genera of fungi were isolated from roots, stems bases and ears of winter barley (Table 2.11), their relative frequency varying with time of sampling as well as with the tissue sampled and site. In 1987, *Cylindrocarpon* was frequent on roots but the main fungi on stem bases were *Alternaria* and *Penicillium*. During 1988, *Cylindrocarpon* was frequently isolated from roots and, at a lower level, stems at the first sampling date but its population declined at later times when *Mucor* became more prevalent on stems. The most prevalent fungus on ears was *Cladosporium* at the three sites. Other organisms with recorded high frequencies on ears were *Epicoccum* at Fife, and *Septoria* and *Penicillium* at the Borders site, while *Alternaria* occurred at moderate levels at all sites. Recognized pathogenic species were *Rhizoctonia tritici*, a crown rot pathogen, and *Septoria nodorum* which causes glume blotch. Fungi occurring very occasionally are indicated in Table 2.10.

TABLE 2.11. Percentage frequency of isolation of different fungi from winter barley roots, stems and ears from four sites, 1987-1988 sampled at different dates (averaged for different cultivars, fungicide treatments and isolation media).

FUNGAL SPECIES	4-7 APRIL		14-17 JUNE			6-10 AUGUST		
	ROOT	STEM	ROOT	STEM	EAR	ROOT	STEM	EAR
1987 (BUSH - cv. Igri)								
Alternaria sp.	-	-	-	-	-	<1	11	-
Cylindrocarpon sp.	-	-	-	-	-	30	5	-
Mucor sp.	-	-	-	-	-	1	5	-
Penicillium sp.	-	-	-	-	-	7	12	-
Rhizoctonia sp.	-	-	-	-	-	2	4	-
1988 (BUSH - cvs Magie and Plaisant)								
Alternaria sp.	0	<1	<1	<1	6	-	-	-
Cladosporium sp.	3	5	1	6	47	-	-	-
Cylindrocarpon sp.	12	4	2	1	0	-	-	-
Epicoccum sp.	0	0	1	<1	6	-	-	-
Mucor sp.	1	3	4	36	0	-	-	-
Penicillium sp.	7	5	<1	<1	3	-	-	-
Rhizoctonia sp.	5	4	<1	0	0	-	-	-
Scytalidium sp.	9	17	<1	<1	0	-	-	-
Trichothecium	2	2	0	<1	0	-	-	-
1988 (BORDERS-cvs. Magie and Plaisant)								
Alternaria sp.	0	0	0	0	7	-	-	-
Cladosporium sp.	4	5	1	7	35	-	-	-
Cylindrocarpon sp.	36	12	6	2	0	-	-	-
Epicoccum sp.	0	0	1	2	6	-	-	-
Mucor sp.	1	2	2	21	1	-	-	-
Penicillium sp.	6	4	1	1	13	-	-	-
Rhizoctonia sp.	<1	<1	1	2	0	-	-	-
Scytalidium sp.	7	12	1	3	0	-	-	-
Septoria sp.	<1	<1	1	<1	30	-	-	-
Trichothecium	1	1	<1	1	0	-	-	-
1988 (FIFE-cvs. Magie and Plaisant)								
Alternaria sp.	0	<1	3	<1	13	<1	<1	5
Cladosporium sp.	2	3	1	2	31	<1	1	32
Cylindrocarpon sp.	12	3	2	4	0	1	<1	0
Epicoccum sp.	1	0	0	0	3	0	0	12
Mucor sp.	1	5	5	34	1	1	9	0
Penicillium sp.	3	1	2	1	<1	11	11	0
Scytalidium sp.	7	7	<1	<1	0	1	3	0
Septoria sp.	12	<1	4	<1	9	<1	<1	

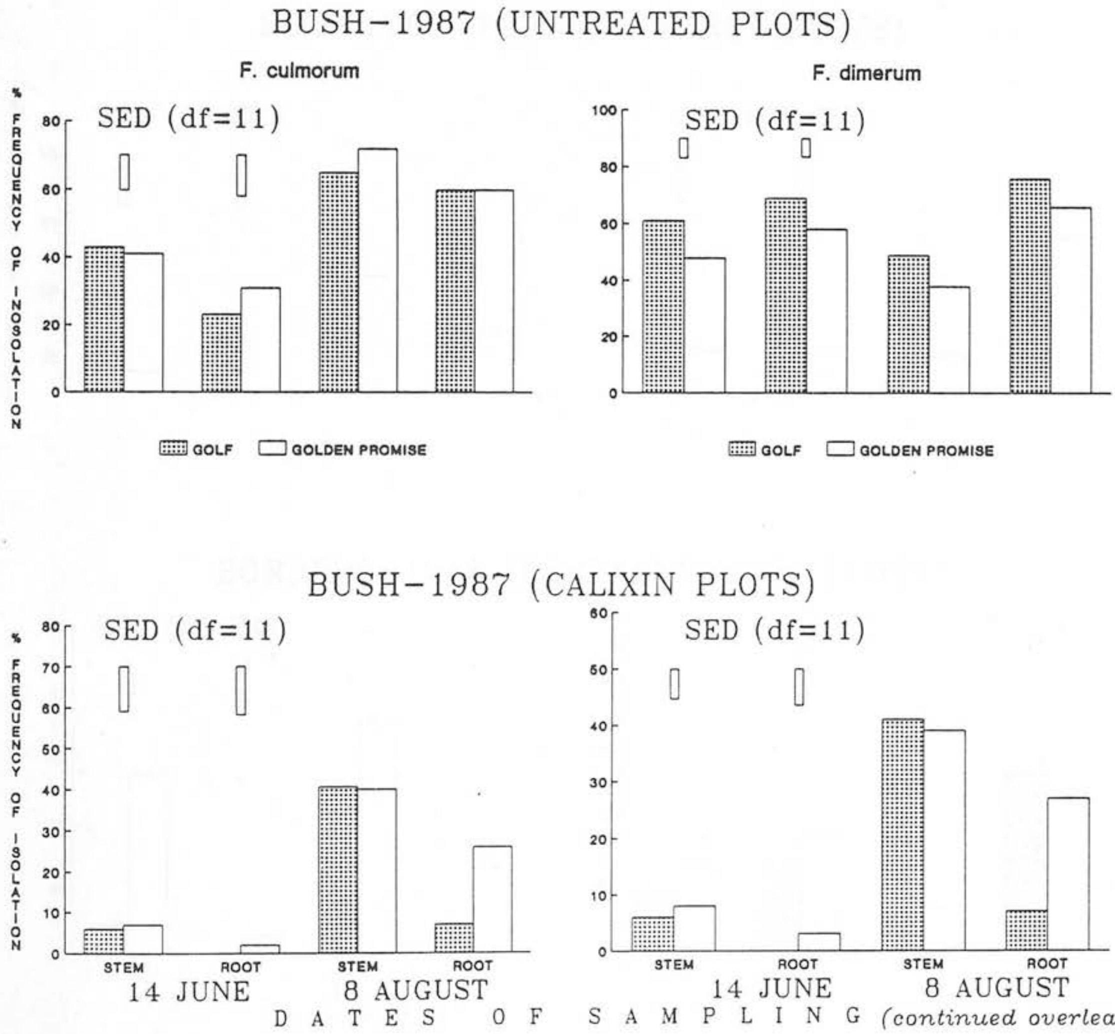
- Not recorded

(b) Spring barley

In the spring barley trials in 1987 and 1988 the cultivars Golf and Golden Promise were used. However cultivar was confounded with fungicide treatment and the only directly comparable plots of the two cultivars are instanced in Figure 2.3. In 1987, for the control plots and those with Calixin it may be seen that there were no statistically significant differences between the two cultivars when the populations of *F. culmorum* and *F. dimerum* were compared. In 1988, only with one treatment, Ferrax + Patrol at the Fife site and the Borders site, were the two cultivars comparable. At the former centre the results for the two cultivars were similar. However in the Borders centre, there was a statistically significant difference in the frequency of *F. culmorum* on stems between the two cultivars but not in the case of *F. dimerum*.

The distribution of the more frequently occurring *Fusarium* species isolated at four sites cropped with spring barley is shown in Table 2.12. *F. culmorum* and *F. dimerum* were recorded most frequently on roots and stems throughout the survey, *F. culmorum* occurring more on stem bases (6-89%) than on roots (2-69%) in the four sites whereas *F. dimerum* was recorded more frequently from roots (17-70%) than from stems (<1-49%). The populations of *F. culmorum* reached a maximum at the second sampling whereas *F. dimerum* was generally most frequent at the first except in one instance. The remaining species of *Fusarium* were usually found only in slight amounts, although *F. nivale* and *F. sambucinum* were recorded on just over 10% of stems sampled from Fife at the second sampling date in 1988. With regard to ear colonization, recorded at the three sites sampled in 1988, *F. culmorum* was a significant component of the grain mycoflora at all three sites (8-46%), while *F. nivale* occurred in abundance

FIGURE 2.3. Percentage frequency of isolation of *F. culmorum* and *F. dimerum* from stems and roots of spring barley cvs. Golf and Golden Promise at different dates of sampling (averaged for isolation media).



(continued overleaf

FIGURE 2.3.
(contd)

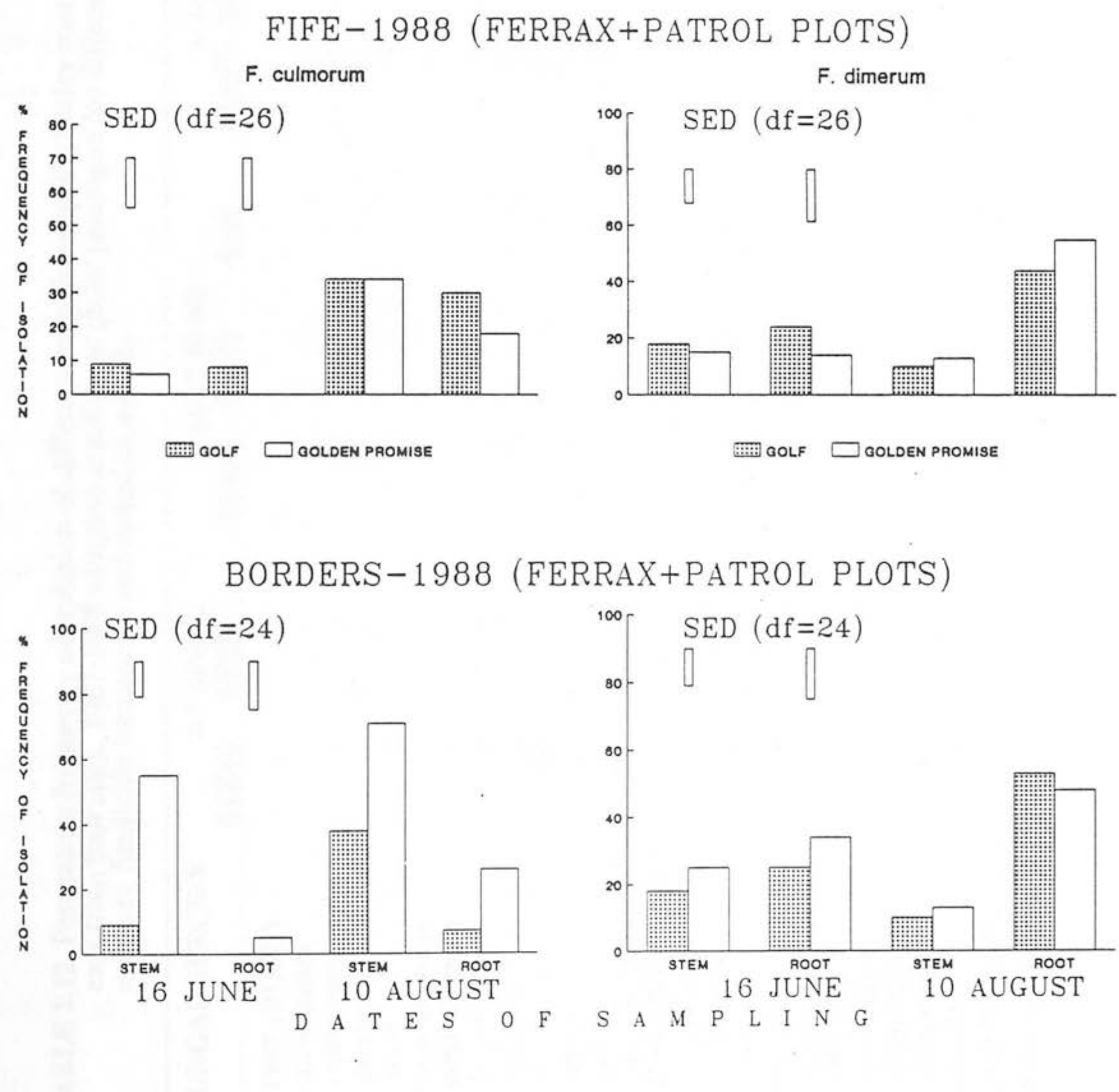


TABLE 2.12. Percentage frequency of isolation of different fungi from spring barley roots, stems and ears from four sites, 1987-1988 sampled at different dates (averaged for different cultivars, fungicide treatments and isolation media).

FUNGAL SPECIES	4-7 APRIL		14-17 JUNE			6-10 AUGUST		
	ROOT	STEM	ROOT	STEM	EAR	ROOT	STEM	EAR
1987 (BUSH)								
F. avenaceum	-	-	1	2	-	2	3	-
F. culmorum	-	-	6	12	-	16	42	-
F. dimerum	-	-	54	49	-	51	38	-
F. poae	-	-	6	2	-	1	2	-
F. sambucinum	-	-	2	3	-	1	3	-
1988 (BUSH)								
F. avenaceum	0	0	<1	3	1	1	1	6
F. culmorum	2	6	69	89	8	38	69	46
F. dimerum	47	35	20	<1	0	39	2	0
F. nivale	1	<1	1	1	2	<1	1	1
F. poae	2	2	0	0	2	0	0	0
F. sambucinum	1	3	7	5	0	2	7	2
1988 (BORDERS)								
F. avenaceum	0	<1	3	2	2	-	-	-
F. culmorum	4	35	15	56	12	-	-	-
F. dimerum	58	33	48	16	0	-	-	-
F. nivale	5	1	2	2	2	-	-	-
F. sambucinum	4	1	<1	2	7	-	-	-
1988 (FIFE)								
F. avenaceum	3	3	<1	1	1	-	-	-
F. culmorum	3	9	25	36	17	-	-	-
F. dimerum	17	19	70	9	0	-	-	-
F. nivale	2	2	2	12	26	-	-	-
F. sambucinum	2	1	1	11	0	-	-	-

- Not recorded

at Fife (26%). *F. avenaceum*, *F. poae* and *F. sambucinum* were isolated from ears at low to moderate levels only. Other species of *Fusarium* occurring in trace or very low levels are listed in Table 2.13 where it may be seen that *F. graminearum*, *F. moniliforme*, *F. poae*, *F. oxysporum* and *F. tricinctum* appeared to be the most widely distributed.

The other genera of fungi recorded relatively frequently included *Cylindrocarpon*, *Mucor* and *Penicillium*, found mainly on roots or stem bases, and *Cladosporium*, *Epicoccum* and *Tricothecium* found mainly on the ears (Table 2.14). Less frequently found fungi included *Alternaria*, *Paecilomyces*, *Rhizoctonia*, *Scytalidium* and *Septoria*, as shown in the table, as well as *Botrytis* (Table 2.13).

(c) Winter wheat

From Table 2.15 it may be seen that the most prevalent *Fusarium* species on roots and stems of winter wheat at the three trials sites were again *F. culmorum* and *F. dimerum* throughout the survey. *F culmorum* showed a higher incidence on stems than on roots and tended to increase with time on older stems and roots. *F. dimerum*, on the other hand, showed a higher incidence on roots than on stems, tending to decline on older stems but increase, at least at two of the sites, in older roots. Other *Fusarium* species found on stems and roots, occurring in slight or moderate amounts, included *F. avenaceum*, *F. poae*, *F. sambucinum* and *F. nivale* , and those found only in slight amounts included *F. sulphureum*, *F. graminearum*, *F. oxysporum* and *F. moniliforme*. Only *F. culmorum*, *F. avenaceum* and *F. nivale* were found on ears at both of the two sites where ear colonization was recorded; *F. nivale* was the most prevalent in Fife and *F.*

TABLE 2.13. Infrequent *Fusarium* species and other fungi isolated from roots, stems and ears of spring barley planted at Bush in 1987 (1), and Bush (2), the Borders (3) and Fife (4) in 1988.

FUSARIUM	ROOT				STEM				EAR		
SPECIES	1	2	3	4	1	2	3	4	2	3	4
F. acuminatum	–	–	–	–	–	+	–	–	–	–	+
F. equiseti	+	–	+	–	+	–	+	–	–	+	–
F. graminearum	+	+	+	+	+	+	+	–	+	+	–
F. moniliforme	+	–	+	–	+	–	+	–	+	–	+
F. poae	+	+	–	+	+	+	–	+	–	+	–
F. oxysporum	+	+	+	+	+	+	–	+	–	–	–
F. semitectum	–	+	+	–	–	–	+	–	–	+	–
F. sulphureum	–	+	–	–	–	+	–	–	–	–	–
F. solani	–	+	+	–	–	+	+	–	–	–	–
F. sporotrichioides	–	–	–	–	–	+	–	–	+	–	–
F. tricinctum	–	+	+	+	–	+	+	+	+	–	+
OTHER FUNGI											
Botrytis	+	–	–	–	+	–	–	–	+	–	+
Green fungus	–	–	–	–	–	–	–	–	–	–	–
White fungus	–	–	–	+	–	–	–	–	+	–	–

-Not present
+Present

TABLE 2.14. Percentage frequency of isolation of different species of fungi from spring barley roots, stems and ears from four sites, 1987-1988 sampled at different dates (averaged for different cultivars, fungicide treatments and isolation media).

Fungal species.	17-25 MAY		3-5 AUGUST			20-26 SEPTEMBER		
	ROOT	STEM	ROOT	STEM	EAR	ROOT	STEM	EAR
1987 (BUSH)								
Alternaria sp.	-	-	4	1	-	1	1	-
Cladosporium sp.	-	-	3	2	-	<1	<1	-
Cylindrocarpon sp.	-	-	5	14	-	5	14	-
Mucor sp.	-	-	4	2	-	0	<1	-
Paecilomyces sp.	-	-	1	5	-	1	<1	-
Penicillium sp.	-	-	4	0	-	1	<1	-
Rhizoctonia sp.	-	-	0	2	-	1	1	-
Scytalidium sp.	-	-	8	4	-	4	10	-
1988 (BUSH)								
Alternaria sp.	0	0	0	0	4	0	0	4
Cladosporium sp.	1	<1	1	0	16	8	5	3
Cylindrocarpon sp.	33	9	1	<1	0	2	<1	0
Epicoccum sp.	0	0	0	0	6	3	<1	18
Mucor sp.	7	8	1	<1	<1	4	14	<1
Penicillium sp.	74	37	<1	0	0	2	0	0
Trichothecium	0	0	0	1	47	0	0	18
1988 (BORDERS)								
Alternaria sp.	<1	<1	0	<1	5	-	-	-
Cladosporium sp.	<1	0	1	1	15	-	-	-
Cylindrocarpon sp.	6	10	14	3	0	-	-	-
Epicoccum sp.	0	0	1	0	37	-	-	-
Mucor sp.	2	5	<1	4	0	-	-	-
Penicillium sp.	10	9	7	1	0	-	-	-
Septoria sp.	0	1	9	3	0	-	-	-
Trichothecium	0	0	2	10	10	-	-	-
1988 (FIFE)								
Cladosporium sp.	<1	1	2	5	21	-	-	-
Cylindrocarpon sp.	11	3	3	0	0	-	-	-
Epicoccum sp.	0	0	3	<1	23	-	-	-
Mucor sp.	3	23	0	18	1	-	-	-
Penicillium sp.	43	33	2	1	0	-	-	-
Scytalidium sp.	6	2	2	7	0	-	-	-
Septoria sp.	10	5	<1	<1	0	-	-	-
Trichothecium	0	0	0	0	5	-	-	-

- Not recorded

TABLE 2.15. Percentage frequency of isolation of different species of *Fusarium* from wheat roots, stems and ears from three sites, 1987-1988 sampled at two different dates (averaged for different fungicide treatments and isolation media).

Fusarium spp.	20-27 AUGUST		19-26 SEPTEMBER		
	ROOT	STEM	ROOT	STEM	EAR
1987 (FIFE-cv. Avalon)					
F. avenaceum	7	2	<1	6	-
F. culmorum	4	25	19	43	-
F. dimerum	41	39	32	21	-
F. graminearum	1	2	<1	<1	-
F. moniliforme	<1	1	0	0	-
F. poae	11	8	20	6	-
F. sambucinum	1	<1	1	1	-
F. sulphureum	1	<1	0	0	-
1988 (FIFE-cv. Longbow)					
F. avenaceum	0	1	4	18	4
F. culmorum	13	16	20	35	2
F. dimerum	40	9	50	2	0
F. nivale	1	0	6	2	12
F. oxysporum	1	1	0	0	0
F. sambucinum	22	27	3	2	0
1988 (BORDERS-cv. Avalon)					
F. avenaceum	2	<1	1	4	3
F. culmorum	26	27	11	57	19
F. dimerum	20	5	57	2	0
F. nivale	4	1	11	4	6
F. sambucinum	4	1	11	4	6

-Not recorded

culmorum at the Borders site, where *F. sambucinum* was also seen. Of the other pathogenic species of *Fusarium, F. graminearum*, and *F. moniliforme* were infrequent.

With respect to fungi other than *Fusarium* species which were recorded, the main root and stem colonizers tended to be *Cylindrocarpon* (mainly on roots) and *Mucor* (mainly on stems). Other species somehow occurring at moderate levels (lower than 10%) on roots and stems included *Scytalidium* and *Penicillium*. The major ear colonizers were *Epicoccum* and *Cladosporium*. Other fungi recorded included *Alternaria*, *Drechslera* and *Penicillium* (Table 2.16).

2.4 DISCUSSION

In assessing the incidence of *Fusarium* species associated with cereal crops in field trials, an introduced bias was towards pathogenic organisms, in as much as plant parts were sampled rather than the general soil environment. Hendrix & Campbell (1973) observed, in the case of *Pythium* species, that saprophytic forms became evident only when the development of effective selective media allowed organisms free from plant tissues to be isolated from the soil. It is possible that a different mode of sampling would have presented a different population structure for *Fusarium* at the different sites. Nevertheless, non-pathogenic *Fusarium* species were recorded. Table 2.17 attempts to indicate the general occurrence of *Fusarium* species classified as aggressive pathogens, weak pathogens or non-pathogenic to cereals according to Booth (1971). It may be seen that non-pathogens occurred only in trace or slight amounts, apart from *F. dimerum* which along with *F. oxysporum*, *F. solani* and *F sulphureum* were found only on roots and stems. *F. acuminatum* and *F sporotrichioides* were isolated only from

TABLE 2.16. Percentage frequency of isolation of different fungi from wheat roots, stems and ears from three sites, 1987-1988 sampled at two different dates (averaged for different fungicide treatments and isolation media).

FUNGAL SPP.	20-27 AUGUST ROOT	20-27 AUGUST STEM	19-26 SEPTEMBER ROOT	19-26 SEPTEMBER STEM	19-26 SEPTEMBER EAR
1987 (FIFE-cv. Avalon)					
Alternaria sp.	3	6	2	7	-
Cylindrocarpon sp.	31	7	17	<1	-
Penicillium sp.	1	2	0	0	-
Scytalidium sp.	4	4	8	13	-
1988 (FIFE-cv. Longbow)					
Alternaria sp.	0	0	2	2	7
Cladosporium sp.	3	3	1	1	45
Cylindrocarpon sp.	8	3	6	1	0
Drechslera sp.	0	0	0	0	2
Epicoccum sp.	0	0	<1	<1	27
Mucor sp.	2	34	1	25	0
Penicillium sp	0	2	8	12	<1
Scytalidium sp.	1	2	<1	0	0
Septoria sp.	8	4	<1	0	0
1988 (BORDERS-cv. Avalon)					
Alternaria sp.	1	<1	<1	2	6
Cladosporium sp.	<1	6	1	1	34
Cylindrocarpon sp.	24	4	2	0	0
Epicoccum sp.	2	6	0	0	33
Mucor sp.	4	29	<1	7	0
Penicillium sp.	9	11	17	9	<1
Scytalidium sp.	2	0	0	0	0
Septoria sp.	2	4	0	0	0

- Not recorded

TABLE 2.17. Relative frequency of isolation from cereal roots, stems and ears of *Fusarium* species grouped according to their pathogenic behaviour towards cereals (averaged over all sites, sampling dates and experimental treatments).

FUSARIUM SPECIES	ROOTS	STEMS	EARS
PATHOGENS*			
F. culmorum	+++	+++++	+++
F. nivale	++	++	+++
F. avenaceum	++	++	++
F. graminearum	+	+	+
F. moniliforme	+	+	+
WEAK PATHOGENS*			
F. sambucinum	+	+++	++
F. poae	++	+	+
F. equiseti	+	+	+
F. tricinctum	+	+	+
NON-PATHOGENS *			
F. dimerum	+++++	+++	–
F. acuminatum	–	–	+
F. oxysporum	+	+	–
F. semitectum	+	+	+
F. solani	+	+	–
F. sporotrichioides	–	–	+
F. sulphureum	+	+	–

*According to Booth (1971)
Scale representing:

–	Not found
+	0.1 to 1.0%
++	1.1 to 5.0%
+++	5.1 to 25%
++++	25.1 to 40%
+++++	40.1 and over

ears and *F. semitectum* occurred in trace amounts on all plant parts. The so-called weak pathogens, included *F. equiseti* and *F. tricinctum* which were found at similar low levels on roots, stems and ears of cereals. *F. poae* was found on all plant parts to some extent but mainly on roots but *F. sambucinum* was more prevalent on stems and ears than on roots. Pathogenic *Fusarium* species were distributed over the plant to a similar extent or were more frequent on stems, *F. culmorum*, or on the ears, *F. nivale*.

In assessing the four media used to isolate fungi, large significant differences in the incidence of the most prevalent *Fusarium* species were observed only between MRB and PPA, particularly with respect to *F. dimerum* which developed colonies very frequently on PPA but occurred only very occasionally on MRB. McMullen & Stack (1983), reported that MRB medium enhanced the isolation of *Fusarium* species especially from roots. The *Fusarium* mycoflora they tested did not include *F. dimerum* and this may have accounted for their better results with MRB. However it may be noted that MRB also gave fewer colonies of *F. culmorum* in the 1987 tests compared with PPA. For our purposes, MRB medium was discarded after assessment for one site only, Bush winter barley plots, 1987, on the basis of several undesirable characteristics, namely low numbers of *Fusarium*, poor *Fusarium* growth and sporulation, and failure to eliminate or restrict growth of other fungi such as *Mucor* and *Penicillium* which may have influenced the recovery of *Fusarium*. Moreover, the preparation of this medium presents difficulties in preparation due to the use of sulphuric acid.

It was observed that, of the isolation media, only PDA induced the characteristic coloration of the *Fusaria* to develop (Plate 2.2). PDA did not stimulate sporulation, probably due to the high concentration in sugars. By reducing its concentration to half the recommended dosage (Rosas & Lennard unpublished data) sporulation was encouraged (Plate 2.3). This modified form of PDA might be useful in assessing the relative frequency of species of *Fusarium* occurring on seed, provided antibiotics are included to restrict growth of bacteria which may inhibit species of *Fusarium*. This approach may not be effective in the case of roots and stems, however, due to the complexity of the mycoflora in the soil.

PPA gave the highest rate of isolation of *Fusarium* species: this might be attributed, at least in part, to the presence of oxgal, which had the effect of restricting colony diameter and allowing a better discrimination between colonies. These results are in agreement with those obtained by Nash and Snyder (1962) and Papavizas (1967).

Although characteristic coloration of the *Fusarium* species was not observed on PPA, nor on DCPA, these media gave a consistent colony morphology (Plate 2.4) and stimulated profuse sporulation to aid in the identification of different species. For these reasons these two media were preferred for the second year of the survey.

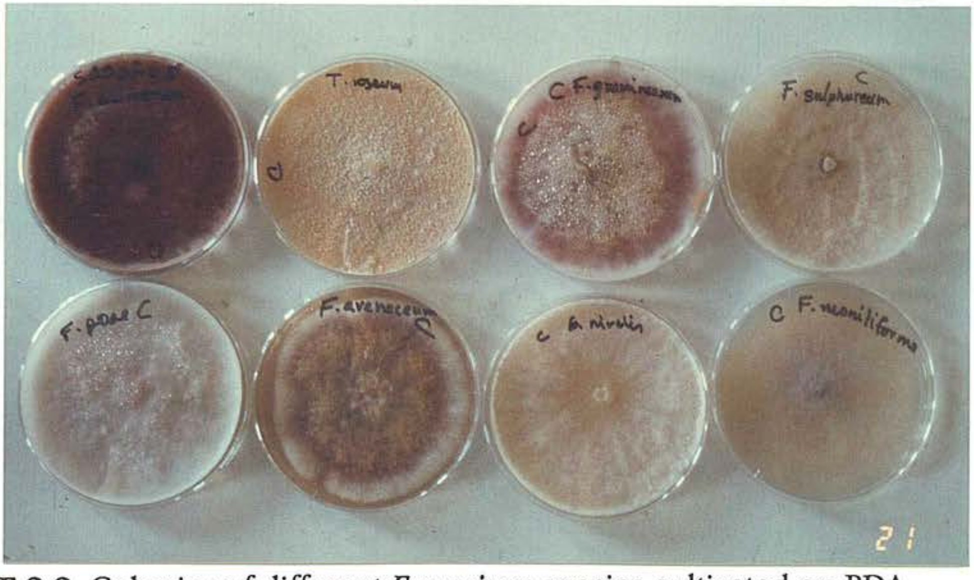


PLATE 2.2. Colonies of different *Fusarium* species cultivated on PDA.

PLATE 2.3. Colonies of *Fusarium* (mainly *F. culmorum*) grown on sugar reduced PDA.

PLATE 2.4. Colonies of *F. culmorum* growing on PPA (above) and DCPA (below).

PLATE 2.5. *F. dimerum* grown on PPA (small colonies in lower position).

The incidence of *F. dimerum* was unexpectedly high and has not previously been reported as a frequent colonizer of cereal plants. In the observations some difficulty was encountered in distinguishing this fungus from *F. nivale*, a commonly recognized parasite of cereals. The following features assisted in differentiating the two species. (a) *F. dimerum*:- On PPA, DCPA and PDA this fungus grew very slowly and formed yeast-like colonies that appeared to be wet and have little visible mycelium (Plate 2.5). The colony colour was beige to orange. The macroconidia were abundant, small, 1-2 septate. Chlamydospores were also observed. (b) *F. nivale*:- *F. nivale* grew more quickly and had a felted aerial mycelium. The colonies varied in colour from white at first to pink-orange as the sporodochia appeared. The macroconidia were bigger than *F. dimerum* and 1-3 septate. No chlamydospores were observed.

It should be noted that two of the media selected for the study were designed to favour *Fusarium* species and this might have influenced the balance of other genera of fungi that were observed. Moreover, it should be noted that PDA, a general isolating medium allowing the most profuse growth of saprophytic fungi, might have masked the presence of slower growth of potentially pathogenic fungi of cereals such as *Septoria* and *Drechslera* that have in other instances been often recorded from stem bases and roots (Butler, 1959; 1961; Fenster, Boosalis & Weihing, 1972; Hill, Fernandez & McShane, 1983). Although symptoms of *Gaeumannomyces graminis* infection were observed visually on the stems of wheat in the field, this fungus was not isolated in pure culture. This was not unexpected, since it is difficult to isolate in competition with other fungi and would not necessarily be found by the media used. In some trials other workers had carried out visual assessments of eyespot caused by *Pseudocercosporella herpotrichioides* which was not indicated to be present by the methods followed in this work. No visual assessments were attempted in the present studies although plants with brown roots and stem bases were often observed. These symptoms were more frequent in the second and third dates of sampling when *F. culmorum*, and *F. sambucinum* in some cases, were more often isolated.

The influence of climatic factors on the prevalence of pathogenic *Fusarium* species on cereals has been studied by different workers throughout the world (Millar & Colhoun, 1969b; Colhoun, 1970; 1973; Mesterhazy, 1974; Cook, 1981a; 1981b; Burgess, Nelson & Toussoun, 1982). Colhoun (1973) reported that low temperatures resulted in much seedling blight caused by *F. nivale*, while at higher temperatures little occurred. *F. nivale* was more prevalent at the Fife site than at other centres and this may be linked with a weather factor. This fungus was more often found on stems and ears than on roots in keeping with the finding of several workers (Millar & Colhoun, 1969a; 1969b; Malalasekera, Sanderson & Colhoun, 1973). The low incidence of *F. nivale* on roots seems to be due to the inability of the fungus to compete with other more competitive fungi such as *F. culmorum*, *Mucor*, *Trichoderma* and many others which are able to produce chlamydospores, sclerotia or antibiotics. According to Colhoun (1973), *F. culmorum* and *F. graminearum* occur more frequently at temperatures between 12 and 22^{o}C than at lower temperatures although he suggested that soil moisture, i.e. dry soils, had a greater influence. Our data of Tables 2.9, 2.12 and 2.15 suggest that *F. culmorum* on roots and stems was only slightly affected by the weather and soil conditions prevalent during this two-year survey as its levels were more or less similar at the different sampled sites. A different situation was found in the case of ears which showed a greater variation in infection levels, which may be due to the more variable nature of the microclimatic away from ground level and to its greater influence on the process of ears colonization. *F. graminearum* levels were low as expected for this fungus which is mainly a cereal colonizer of warmer regions (Burgess, Dodman, Pont & Mayers, 1981; Cassini, 1981; Cook, 1981a; 1981b). *F. avenaceum* showed generally only a low incidence, moderate amounts occasionally occurring on stems and ears. This fungus is reported to be less pathogenic than *F. culmorum* or *F. nivale* (Cook, 1981a). One unexpectedly frequent *Fusarium* was *F. sambucinum* which seemed to increase on aerial parts of the plants relative to its incidence on roots. This fungus has been reported as the cause of a root and seedling rot chiefly from eastern Europe and USSR and Gordon (1952) reported its rare occurrence on cereal seeds in Canada.

In recognizing *F. culmorum* as the most prevalent *Fusarium* pathogen in the survey, spring barley seemed to be particularly susceptible to the colonization of the aerial parts by this fungus. According to several reports in Scotland (Noble & Montgomerie, 1955; Foister, 1961; Noble, 1970), seedling blight, foot and root rots, and head blight are mainly caused by *F. nivale* in the first place and if the weather is favourable, warm and dry, *F. culmorum* and *F. avenaceum* may cause some disease (Rennie, 1989: Personal communication). *F. nivale* has frequently been isolated from seeds by workers at the Official Seed Station at East Craigs, Edinburgh. The high incidence of *F. culmorum* compared with *F. nivale* in our studies may be related to the above average temperatures (ESCA weather date sheets, 1987-1988) which prevailed over the years of the trials. In warmer climates as in Mexico, Australia and USA, *F. graminearum* and *F. culmorum* are the main cause of crown rot and head blight or scab (Burgess *et al.* 1975; Cook, 1981a; Ireta, 1986). In the United Kingdom *F. graminearum* has rarely been recorded as was the case in our studies. Although *F. poae* was more frequently isolated than *F. nivale* in 1987 from Fife, it is normally regarded as a weak pathogen (Booth, 1971). Tests on the relative pathogenicity of the main species isolated in the present study are considered in Section 4.

With regard to the occurrence of fungal species other than *Fusarium* organisms *Cylindrocarpon* and *Penicillium*, which occur mainly as saprophytes, were prevalent on roots and, along with these species *Mucor* was found frequently on stems. On ears the saprophytes *Cladosporium* and *Epicoccum* were widespread while *Trichothecium (T. roseum)* was notable for its occurrence on the ears of spring barley at all three sites. This fungus is of interest in relation to cereals in that it has exhibited antagonism to *F. graminearum* (Beratlief & Tircomnicu, 1979), has been associated with the production of the toxic metabolite, trichothecin, in wheat kernel samples (Ishii, Kobayashi, Ueno & Ichinoe, 1980) and has caused an ear kernel rot in maize (Kumar & Shetty, 1985). It has therefore been studied further in some of the experimental work with *Fusarium*.

SECTION 3

FIELD AND LABORATORY STUDIES ON THE RESPONSES OF *FUSARIUM* SPECIES TO FUNGICIDES

3.1 Introduction

The previous Section presents the results of a survey of the incidence of *Fusarium* species and other fungi isolated from cereal plants grown in ESCA field trials in the east of Scotland during 1987 and 1988. These trials were concerned with the assessment of the performance of various fungicide treatments for the control of mainly leaf diseases and eyespot. The present Section considers the development of the use of fungicides in cereals and its significance with respect to *Fusarium* disease problems.

Chemical control is a highly visible, effective, and at times, controversial technique to manage plant diseases. The intensity of use of fungicides varies with crop and cropping system. Some crops, such as fruits and certain vegetables, have a long history of fungicide use in the field but others, such as cereals, have only recently been treated on a commercial scale with field fungicides, although seed treatment has been used since early times on cereal seed. Within the present century organomercury seed dressings have been widely used to protect cereals against covered smut fungi and *Pyrenophora* species, and represent one of the few chemical groups aimed directly against *Fusarium* diseases of cereals. Clark (1981) carried out an experiment using organomercury seed treatment on barley seed artificially inoculated with *Fusarium* species and found that seed treatment markedly increased yields (25%). In growth room experiments, treatment of wheat seed with phenyl mercuric acetate significantly reduced seedling disease caused by soil-borne *F. culmorum*, *F. nivale* and *F. avenaceum* in inoculated soil (Bateman, 1977). He also reported that seed treatment improved the low germination caused by *F. culmorum*, regardless of conditions that favour the disease, but did not affect the reduced seedling vigour caused by *F. nivale*, apparently because this fungus produced more deep-seated infection and, therefore, was less accessible to the fungicide (Bateman, 1976). In the 1960s the introduction of systemic fungicides made feasible the control of seed-borne fungi carried internally, and which could not be reached by superficial disinfectants such as the organomercurials. The oxathiin compound, carboxin, became used for this purpose against loose smut of barley and wheat. Abou-Heilah (1984) found that the numbers of isolated fungi were greatly reduced when seeds were treated with various fungicides, including systemics, before placing them on the agar plates. Complete inhibition of growth was recorded in the case of *Alternaria chlamydospora, A. terreus, Drechslera specifer, Fusarium* species and *Humicola grisea* with the systemics benomyl and carbendazim. Nuarimol was tested by Casanova, Dohler, Farrant & Ratwell (1977) as a fungicide for seed dressing of, and foliar applications to, cereals in Europe. They found that in glasshouse and field experiments the compound showed, at a low rate of use, control of the major seed-borne diseases of barley, namely *F. nivale, Pyrenophora graminea* and *Ustilago* species, and the foliar pathogen *Erysiphe graminis*. Guazatine has been shown to be effective against *Fusarium* by Bartlett & Ballard (1975) and Clark (1977). The triazole fungicide, triadimenol, as a seed dressing along with the MBC fungicide, fuberidazole, has been found to give good control of *Fusarium* species (Wainwright, Rollett & Morris, 1979).

In the 1960s systemic fungicides were developed to counteract not only seed-borne diseases but also diseases transmitted in other ways: two of the earliest were ethirimol applied as a seed dressing or spray to control cereal mildew and tridemorph, used as a spray primarily for the control of mildew (Evans, 1971). A more extensive use of fungicides on cereals from the early 1970s in Britain coincided with this introduction of systemic fungicides coupled with the intensification of cereal production. Fungicides became extensively used against the air-borne diseases mildew, rusts and other leaf diseases, and also against eyespot. Some were seed applied others sprayed onto crops. However, there has been little use of fungicides aimed specifically or directly against *Fusarium*, other than seed-applied chemicals.

Some side effects of the use of fungicides are undesirable, including hazards to human health, consequences to non-target pathogens or other microorganisms, and resistance to the chemical in the pathogen population.

The acute hazard to humans of some disease management chemicals has been readily apparent. Misuses of toxic chemicals has sometimes had tragic consequences. For example, in several different instances people have been poisoned when they mistakenly consumed seed treated with mercury-based fungicides used to suppress damping-off.

Despite the recent upsurge of interest in the environment, fungicides have continued to play an expanding role in the control of plant diseases. The full significance of the use of such chemicals seems, however, to be often poorly appreciated. Particular effects against organisms other than the target pathogen and its host are not always known and in some cases treatment may result in secondary pests becoming more important. Application of a chemical that allows plants to retain more foliage, and alters the microclimate, can favour pathogens that are generally not so important on untreated plants. The increased use of narrow spectrum fungicides is a phenomenon of the 1970s, may still have significance for some non-target pathogens. Where benzimidazole fungicides (most effective against hyaline-spored Ascomycetes) have been applied, members of the Oomycetes are relatively unaffected and the disease problems they cause have been extended (Dekker, 1973): for example, *Pythium* blight of turf and *Pythium* stem rot of cowpea were more severe in the presence of benzimidazole fungicides than in their absence (Warren, Sanders, Cole & Duich, 1976; Williams & Ayanaba, 1975). Many Basidiomycetes are less sensitive to benzimidazoles than are most Ascomycetes, and application of these fungicides to suppress diseases induced by Ascomycetes can increase disease induced by Basidiomycetes. For example, although benzimidazole fungicides suppressed the pathogenic activities of *Pseudocercosporella herpotrichoides* and *Fusarium* species on rye and increased yield, the severity of sharp eyespot disease (*Rhizoctonia tritici*) increased about 10-fold (Platenkamp & Bollen, 1973; Van der Hoeven & Bollen, 1972; 1980). Yarham and Giltrap (1989) attributed the explosion of net blotch (*Pyrenophora teres*) in winter barley in the late 1970s, in part, to the widespread use of triadimefon which controlled most other diseases, leaving the leaf open to attack by *P. teres*. Dickinson & Wallace (1976) found that repeated sprays of tridemorph appeared to inhibit only the actinomycete-like organisms of the phyllosphere microbial flora but that benomyl and more particularly zineb on its own and a mixture of zineb and carbendazim markedly restricted the development of many yeasts and filamentous species. *Alternaria, Cladosporium* and several types of ascospores and conidia were all inhibited by the non-specific zineb.

Fungicide resistance, i.e. a change to reduced sensitivity to a fungicide, in fungal pathogens, has become an important problem since the widespread use of systemic fungicides began in the early 1970s. Although inorganic, broad spectrum fungicides have been used widely for many years, few pathogens have shown increased resistance to them to account for reduced levels of practical control. For example, resistance to sulphur, the oldest and one of the broadest spectrum fungicides, has not been an important practical problem (Ogawa, Gilpatrick & Chiarappa, (1977). Non-systemic organic compounds have also been used extensively but with relatively few instances of the emergence of fungicide resistance problems (Andrilenas, 1974; 1975). One notable exception to the resistance to organic mercury compounds in *Pyrenophora avenae* reported by Noble, MacGarvie, Hams & Leafe (1966) and later in *Pyrenophora graminea* (Jones, Slade & Birks, 1989). Additionally, localized problems have resulted from resistance to non-systemic fungicides such as dodine in *Venturia inaequalis*; dinocap in *Sphaerotheca fuligena*; Dyrene in *Sclerotinia homeocarpa*; hexachlorobenzene in *Tilletia foetida*; and triphenyltin compounds in *Cercospora beticola* (Georgopoulos, 1969; Giannopolitis, 1978; Nicholson, Meyer, Sinclair & Butler, 1971; Szkolnik & Gilpatric, 1969; 1973)

Resistance to broad-spectrum fungicides has been more frequently demonstrable in laboratory assays than in the field. Resistance to PCNB was detected in isolates of *Sclerotium rolfsii* but most of the isolates tended to be less fit pathogenically than sensitive isolates (Georgopoulos & Zaracovitis, 1967). Ogawa *et al.* (1977) cite 15 additional examples where fungi resistant to non-systemic fungicides have been either induced or identified, but where resulting yield loss has not been demonstrated.

Since the widespread use of narrow spectrum, systemic chemicals began the problem of fungicide resistance has grown rapidly to one of major concern. Because of specific biochemical modes of action of systemic fungicides, simple mutations in the target pathogen effect insensitivity. Consequently, resistance to these fungicides has developed more readily than has resistance to the older, broad-spectrum protectant fungicides. Systemic compound have been used extensively because of several advantages relative to non-systemic compounds. They are effective at low doses, more persistent and they can inhibit pathogens in infected tissue.

Among the most dramatic examples of rapid evolution of resistance in pathogen populations are with benzimidazoles (e.g., benomyl) and more recently with phenylamides (e.g. metalaxyl) (Milgroom, Levin & Fry, 1989). According to Ogawa *et al.* (1977), of 37 cases where resistance to specific and/or systemic fungicides led to poor disease control in the field, 33 involved benzimidazole fungicides apparently because resistance to these fungicides occurs at a low incidence in natural populations of some pathogens normally sensitive to them. Within a few years after intensive use of these fungicides began, resistant pathogens increased in number and frequency, resulting in a breakdown in disease suppression. The rapid build-up of resistance to phenylamides was especially troubling because laboratory studies had predicted the risk of resistance was not great (Staub, Dahmen, Urech & Schwinn, 1979). In field populations, the evolution of fungicide resistance is a simple process: a low frequency of resistance is present because of mutation; when the population is exposed to a selective fungicide, the resistant types increase in number faster than the sensitive types because they are not inhibited by fungicide; and finally, additional fungicide applications have little effect on controlling disease because most of the population is resistant. Although this process was rapid for many occurrences of resistance to benomyl in *Botrytis cinerea* or to metalaxyl in *Phytophthora infestans*, resistance to these and other fungicides has develop more slowly in some pathogens. For example, triazole resistance in *Erysiphe graminis* f. sp. *hordei* (Wolfe, 1985) or benzimidazole resistance in *Pseudocercosporella herpotrichoides* (Fehrmann, 1985) has not evolved as rapidly. Other pathogens have not developed detectable levels of resistance in the field even though resistant types can be found easily in the laboratory (e. g., carboxin resistance in the smut fungi). Although the rate of development of resistance may be correlated to fungicide groups and the genetics of resistance (Georgopoulos & Skylakakis, 1986), these correlations *per se* do not explain the dynamics of resistance in a population. Clearly there are more factors to consider in order to understand the rate at which resistance evolves in a population. Among the factors are initial frequency of resistance, fungicide efficacy, fungicide coverage, fungicide weathering, and various epidemiological factors, such as apparent infection rate and latent period (Delp, 1980; Josepovits & Dobrovolsky, 1985; Kable & Jeffery, 1980; Levy & Levy, 1986; Levy, Levy & Cohen, 1983; Skylakakis, 1981; 1982). The influence of most factors is manifested in population growth rates. This type of simplification has made it possible to derive some generalized management strategies for reducing the built-up of resistance (Milgroom & Fry, 1988).

With respect to fungicide resistance in *Fusarium* pathogens of cereals, Chastagner & Vassey (1982) found that 21 of 24 isolates of *F. nivale* obtained from two lawns where applications of iprodione failed to control disease development were able to grow on PDA amended with iprodione. Locke, Moon, & Evans (1987) found that most isolates (92%) of *F. nivale* obtained from a survey of wheat crops in England and Wales were resistant to the MBC fungicide benomyl and in a recent review of work on *Fusarium* diseases of cereals (Jenkins, Clark & Buckle, 1988) reference is made to a survey of wheat in which carbendazim (MBC) resistance was found in *F. nivale* isolates (100%), *F. poae* (56%), *F. culmorum* (14%) and *F. avenaceum* (7%) Resistance to MBC in field populations of *F. nivale* and *F. culmorum* has been listed in an ADAS leaflet (Anon, 1988).

In considering the relationship between *Fusarium* diseases in cereals and fungicide use, relatively little work has been reported. Partial control of these diseases can be achieved by seed treatment, with for example organomercurials, or by spray applications of MBC generating compounds (Jones & Clifford, 1983) and prochloraz (Jenkins, Clark & Buckle, 1989): however the causal fungi have not been regarded to be of sufficient significance to warrant much attention although they are increasingly recognized to be of potential importance. Taking into account the prevailing widespread use of fungicides in cereal fields to control leaf diseases and eyespot, the main purpose of the experimental studies in this Section were to assess the effects of various fungicide treatments on the incidence of *Fusarium* species and associated organisms, taking advantage of fungicide trial plots established in the east of Scotland by the East of Scotland College of Agriculture. A further aim was to study the extent of inter- and intra-specific variation in sensitivity of *Fusarium* isolates from cereals to selected cereal fungicides, using *in vitro* tests.

3.2 MATERIALS AND METHODS

3.2.1 Fungicide field trials.

In Section 2, the results are given of a survey carried out in 1987 and 1988 of the incidence of *Fusarium* species and other fungi on cereal plants grown in trial plots located at different sites in the east of Scotland. The trials had been laid out to test various fungicide treatments aimed primarily for the control of mildew, rusts or eyespots. Details of the materials, trial lay-outs and methods used in these trials are given in Section 2. In Table 3.1 a list of the commercial names of the fungicides tested and the active ingredients is presented: in subsequent references the commercial names are mainly used to avoid unwieldy descriptions of mixtures. The fungicides applied in any one trial are intimated in the tables of

TABLE 3.1. List of fungicides used in the cereal crops field trials during 1987 and 1988 in the east of Scotland.

COMMERCIAL NAME	ACTIVE INGREDIENT	CHEMICAL GROUP
Bardew	tridemorph	Morpholine
Bavistin	carbendazim	Benzimidazole
Bayfidan	triadimenol	Triazole
Bayleton	triadimefon	Triazole
Baytan	triadimenol	Triazole
	fuberidazole	Benzimidazole
Bravo	chlorothalonil	Chlorobenzene
Calixin	tridemorph	Morpholine
Chiltern super six	sulphur	Inorganic
Corbel	fenpropimorph	Morpholine
Cosmic	carbendazim	Benzimidazole
	tridemorph	Morpholine
	maneb	Dithiocarbamate
Delsene	carbendazim	Benzimidazole
	maneb	Dithiocarbamate
Dorin	triadimenol	Triazole
	tridemorph	Morpholine
Early impact	flutriafol	Triazole
	carbendazim	Benzimidazole
Ferrax	flutriafol	Triazole
	thiabendazole	Benzimidazole
	ethirimol	Aminopyrimidine
Hispor	propiconazole	Triazole
	carbendazim	Benzimidazole
Impact excel	flutriafol	Triazole
	captafol	Phthalimide
Mistral	fenpropimorph	Morpholine
Patrol	fenpropidin	Morpholine
Sirocco	iprodione	Dicarboximide
	fenpropimorph	Morpholine
Sportak	prochloraz	Imidazole
Sportak alpha	prochloraz	Imidazole
	carbendazim	Benzimidazole
Sprint	prochloraz	Imidazole
	fenpropimorph	Morpholine
Tilt	propiconazole	Triazole
Tilt turbo	propiconazole	Triazole
	tridemorph	Morpholine
A696 OC	Test fungicide	
A7114 A	Test fungicide	
ACF 225	Test fungicide	
ESCA	Test fungicide	
ESCA 88 F1	Test fungicide	
ESCA 88 F3	Test fungicide	
MIX1	Test fungicide	
MIX2	Test fungicide	
MIX3	Test fungicide	
MIX4	Test fungicide	
MIX5	Test fungicide	
MON 17111	Test fungicide	
N 7872	Test fungicide	
Mixture	Test fungicide	

results.

3.2.2 Laboratory tests on the fungicide sensitivity of different *Fusarium* species.

Cultures of particular *Fusarium* species isolated from the fungicide field trials during the 1987-1988 survey were tested *in vitro* for their response to exposures to different dosages of Baytan (triadimenol ai 25% w/w; fuberidazole ai 3% w/w) and Dorin (triadimenol ai 12.5%; tridemorph ai 37.5%). The species included were *F. avenaceum, F. culmorum, F. dimerum, F. graminearum, F. moniliforme, F. nivale, F. poae, F. sambucinum, F. sulphureum* and, along with these, *Trichothecium roseum*. Several different isolates of *F. culmorum* and *F. nivale* were used in tests to assess any intra-specific variation in response to fungicide. In the case of *F. culmorum* only Baytan was used but for *F. nivale* both Baytan and Dorin were included.

PDA was suspended in distilled water at the rate of 39 g/litre and was dispensed and sterilized by autoclaving for 15 minutes (20 **psi** at 121^{o}C). Stock solutions of each fungicide were prepared with the following concentrations of triadimenol, following a similar procedure to that recommended by ADAS for benomyl sensitivity testing:

(i) Stock solution A: 0.67 g triadimenol in 250 ml of 95% ethyl alcohol.

(ii) Stock solution B: 6.7 g of triadimenol in 50 ml of 95% ethyl alcohol.

Different volumes of stock solutions A and B were added to 100 ml of agar to give final concentration of triadimenol ranging from 1 ug/ml to almost 1000 ug/ml as shown in Table 3.2.

The analyses of the data were based on the methods of Locke *et al.* (1987), using ED_{50} values derived from regressions of colony growth rate against triadimenol concentration and minimum inhibitory concentration.

Table 3.2. Triadimenol concentrations used in the *in vitro* study.

Volume of stock solution/ 100 ml agar	Final concentration of fungicide (ug/ml)
Stock solution A	
Control - no fungicide	0
A1 - 0.1 ml	1
A2 - 0.5 ml	5
A3 - 2.5 ml	25
A4 - 5.3 ml	50
Stock solution B	
B - 2.0 ml	980

The fungicide solutions were added to the molten agar after cooling to a temperature of 45°C and poured into disposable Petri dishes (10 plates/200 ml agar). To determine the sensitivity of the different isolates and species of *Fusarium*, they were grown on PDA and on PDA amended with either Baytan or Dorin. Mycelial plugs (5 mm in diameter) of each isolate or species grown on PDA were transferred to the centre of each test medium. The mycelial discs were put upside down on the agar surface and the incubated at a temperature of 20°C. Two measures of the radial growth were carried out in each of three replicates for each fungal isolate and fungicide concentration, one after 4 days and the second after 7 days. Data of readings were analysed and compared using non-linear regression.

3.3 RESULTS

3.3.1. Fungicide field trials

The responses of *Fusarium* and other non-target species are considered only in those cases where the average incidence of any member of this group was at least 5% in a trial. The analyses of the data in these instances is presented for fungicide effects in Appendices II to V and the results summarized in Tables 3.3 to 3.14, with treatment plot results being expressed as a percentage of the controls. The results are an average of different times of assessment to indicate overall trends, as fungicide applications were mainly made before assessments were begun. Those trials, where there were no untreated control plots, namely all 1988 winter barley trials and the 1988 Borders spring barley trial, are excluded from consideration. The results are given in order of the main fungi present and their occurrence on roots, stems and ears.

Fusarium culmorum :

In the 1987 winter barley trial at Bush there was a variable incidence of root infection by *F. culmorum* and, while the fungus was not isolated from plots treated with Dorin, there was no evidence of clear beneficial effects from other fungicide treatments (Table 3.3). However, over the spring barley and winter wheat trials at the three centres over the 2 years there was a general trend for fungicide treatments to reduce incidence of *F. culmorum* on roots (Tables 3.4 & 3.5). In the case of spring barley (Table 3.4), all fungicide treatments significantly reduced levels of infection at the Bush site in 1987 on both Golf and Golden Promise and in 1988 the reductions were again significant at the Bush site, but only for Golf. At the Borders and Fife sites in 1988, fungicide effects were not significant but in all instances fungicide treatments gave a reduced incidence compared with control plot levels. Fungicides treatments in winter wheat trials all

TABLE 3.3. Incidence of *F. culmorum* on roots and stems of winter barley cv. Igri in relation to fungicide treatment expressed as a percentage of incidence for control plots (averaged for time of assessment and isolation medium)-Bush 1987.

FUNGICIDE TREATMENT	ROOTS	STEMS
Control	100(31)	100(64)
Baytan(s)	60	47-
Ferrax(s)	36-	23-
Tilt	32-	18-
Tilt turbo	125	21-
Dorin	0-	18-
Sportak + Bardew	56	27-
Cosmic	20-	14-
Cosmic + Bayfidan	8-	19-
Sirocco	20-	14-
Sirocco + Bayfidan	24-	27-
Mixture (test)	48	35-
Mixture (test)	20-	27-

- Significantly less than controls (Appendix II)
+ Significantly more than controls
Actual % frequency of control given in brackets
(s) Seed application

TABLE 3.4. Incidence of *F. culmorum* on roots of spring barley (cvs. Golf (G) and Golden Promise (GP)) in relation to fungicide treatment expressed as a percentage of incidence for control plots (averaged for time of assessment and isolation medium).

FUNGICIDE TREATMENT	Bush/87 G	Bush/87 GP	Bush/88 G	Bush/88 GP	Fife/88 G	Fife/88 GP
Control	100(49)	100(51)	100(47)		100(33)	
Ferrax(s)	12–					
Ferrax(s) + Patrol	16–	31–			14	27
Baytan(s) + Dorin		8–				
Dorin			17/31–		52/70	
Sprint			34/70–			
Calixin	6–	25–				
Bayfidan + Corbel		8/12–				
Calixin + (2) Corbel				81/85		12/12
Corbel + Dorin						9
Dorin + Corbel						21
Mon (Test)			53–	94	70	58
A7114 (Test)				70–		24
ACF (Test)				96		24

- Significantly less than controls (Appendix IV)
+ Significantly more than controls
Actual % frequency of control given in brackets
(s) Seed application

TABLE 3.5. Incidence of *F. culmorum* on roots of winter wheat in relation to fungicide treatment expressed as a percentage of incidence for control plots (averaged for time of assessment and isolation medium).

FUNGICIDE TREATMENT	Fife 87 Avalon	Fife 88 Avalon	Borders 88 Long bow
Control	100(45)	100(49)	100(51)
Sportak alpha + Impact Excel	20-		2-
Baytan(s) + Sportak alpha/ Impact Excel	24-	12-	8-
Baytan(s) + Sportak + Impact excel		10-	24-
Baytan(s) + Early impact + Impact excel + Patrol		39-	22-
Baytan(s) + Citozyme + Sportak alpha Impact excel			22-
Citozyme + Sportak alpha + Impact excel			10-
Baytan(s) + Sportak alpha + Bayleton	24-		
Baytan(s) + Sportak alpha + ESCA88 F3		8-	
Sportak alpha + ESCA 88 F1		6-	4-
Baytan(s) + Dorin + Sportak alpha + Dorin + Bravo + Dorin	20-		
Sportak alpha + Sprint		6-	76-
Sportak alpha + Sportak	27-		
Sportak alpha + Impact excel		12-	
Sportak + ESCA (test) + Bardew	31-		
Sportak alpha + A 696 OC (test)		20-	
(2) ESCA (test)	18-		
Sportak alpha + Dorin + Dorin + Dorin + Bravo + Dorin + Delsene			4-
Dorin + Bavistin + Delsene + (2) Dorin + Bravo		8-	
(2) N7872 (test)	24-		
Hispor + (2) Tilt turbo	29-		

- Significantly less than controls (Appendix V)
+ Significantly more than controls
Actual % frequency of control given in brackets
(s) Seed application

showed significantly reduced infection of roots by *F. culmorum* (Table 3.5).

The incidence of *F. culmorum* on stems was invariably reduced by the fungicide treatments on the different cereals at the three sites over the two years (Tables 3.3, 3.6 & 3.7). For winter barley and wheat fungicide effects were usually significant (Tables 3.3 & 3.7) and in the case of spring barley they were mainly significant with the exception of those for Golden Promise at Bush in 1988 and both Golf and Golden Promise at Fife in 1988 (Table 3.6).

In the case of ear inoculation by *F. culmorum* no significant effects of fungicide were observed for any of the spring barley trials (Table 3.8a). However, for winter wheat, only in one case was the frequency of isolation above about 5% and this is indicated in Table 3.8b, which shows that at the Borders site, with two exceptions, fungicide treatments substantially reduced ear infection.

Fusarium dimerum :

With respect to the incidence of *F. dimerum* on roots there was little evidence of any marked effect of fungicide treatment from any of the trials (Tables 3.9, 3.10 & 3.11). With some treatments slight reductions occurred and from others there were increases but generally these effects of fungicide were non-significant. There were, also, relatively few significant effects of fungicide on stem infection by this fungus, the few there were being usually associated with an increased incidence (Tables 3.9, 3.12 & 3.13). As indicated in the previous section there was a zero frequency of isolation of *F. dimerum* from ears on all plots including controls.

TABLE 3.6. Incidence of *F. culmorum* on stems of spring barley in relation to fungicide treatment expressed as a percentage of incidence for control plots (averaged for time of assessment and isolation medium).

FUNGICIDE TREATMENT	Bush 87 G	Bush 87 GP	Bush 88 G	Bush 88 GP	Fife 88 G	Fife 88 GP
Control	100(63)	100(68)	100(69)		100(37)	
Ferrax(s)	62–					
Ferrax(s) + Patrol	38–	55–			43	54
Baytan(s) + Dorin		50–				
Dorin			24/22–		49/63	
Sprint			77/53–			
Calixin	37–	35–				
Bayfidan + Corbel		44/34–				
Calixin + (2) Corbel				86/87		–35/73
Corbel + Dorin						73
Dorin + Corbel						27–
Mon (test)			67–	86	27–	73
A77114 (test)				91		59
ACF (test)				91		65

- Significantly less than controls (Appendix IV)
+ Significantly more than controls
Actual % frequency of controls given in brackets
(s) Seed application

TABLE 3.7. Incidence of *F. culmorum* on stems of winter wheat in relation to fungicide treatment expressed as a percentage of incidence for control plots (averaged for time of assessment and isolation medium).

FUNGICIDE TREATMENT	**Fife 87 Avalon**	**Fife 88 Avalon**	**Borders 88 Longbow**
Control	100(45)	100(49)	100(51)
Sportak alpha + Impact Excel	39-		33-
Baytan(s) + Sportak alpha + Impact Excel	24-	24-	33-
Baytan(s) + Sportak + Impact excel		17-	38-
Baytan(s) + Early impact + Impact Excel + Patrol		40-	37-
Baytan(s) + Citozyme + Sportak alpha Impact excel			26-
Citozyme + Sportak alpha + Impact excel			23-
Baytan(s) + Sportak alpha + Bayleton	29-		
Baytan(s) + Sportak alpha + ESCA88 F3 (test)		15-	
Sportak alpha + ESCA 88 F1 (test)		24-	33-
Baytan(s) + Dorin + Sportak alpha + Dorin + Bravo + Dorin	25-		
Sportak alpha + Sprint		17-	89-
Sportak alpha + Sportak	47-		
Sportak alpha + Impact excel		14-	
Sportak + ESCA (test) + Bardew	46 -		
Sportak alpha + A 696 OC (test)		28-	
(2) ESCA (test)	58-		
Sportak alpha + (3) Dorin + Bravo + Dorin + Delsene			10-
Dorin + Bavistin + Delsene + (2) Dorin + Bravo		21-	
(2) N7872 (test)	72-		
Hispor + (2) Tilt turbo	46-		

- Significantly less than controls (Appedix V)
+ Significantly more than controls
Actual % frequency of control given in brackets
(s) Seed application

TABLE 3.8. Incidence of *F. culmorum* on ears of spring barley (cvs. Golf (G) and Golden Promise (GP)) and wheat (cv. Longbow) in relation to fungicide treatment expressed as a percentage of incidence for control plots (averaged for time of assessment and isolation medium).

(a) SPRING BARLEY

FUNGICIDE TREATMENT	Bush/88 G	Bush/88 GP	Fife/88 G	Fife/88 GP
Control	100(13)	100(13)	100(10)	100(10)
Ferrax(s) + Patrol			230	211
Dorin	217/92		160/20	
Sprint	92/246			
Dorin + Corbel				322
Calixin + Corbel		146		110
Calixin + (2) Corbel		185		144
Calixin + Sprint				
Corbel + Dorin				156
Mon (Test)	233	261	160	270
A7114A (Test)		192		80
ACF (Test)		192		156

(b) WHEAT (cv. Longbow-BORDERS)

Control	100(64)
Baytan(s) + Sportak alpha + Impact Excel	5−
Baytan(s) + Sportak + Impact excel	2−
Baytan(s) + Early impact+Impact Excel+Patrol	86
Baytan(s) + Citozyme + Sportak alpha Impact excel	2−
Citozyme + Sportak alpha + Impact excel	3−
Sportak alpha + Sprint+Delsene	64
Sportak alpha + Impact excel	2−
Sportak + ESCA (test)	5−
Sportak alpha + (3) Dorin + Bravo + Dorin + Delsene	9−

- Significantly less than controls (Appendix V)
+ Significantly more than controls
Actual % frequency of control given in brackets
(s) Seed application

TABLE 3.9. Incidence of *F. dimerum* on roots of winter barley cv. Igri in relation to fungicide treatment expressed as a percentage of incidence for control plots (averaged for time of assessment and isolation medium)- Bush 1987.

FUNGICIDE TREATMENT	ROOTS	STEMS
Control	100(36)	100(38)
Baytan(s)	125	96
Ferrax(s)	90	79
Tilt	111	100
Tilt turbo	108	89
Dorin	125	72
Sportak + Bardew	108	100
Cosmic	122	79
Cosmic + Bayfidan	122	59
Sirocco	119	103
Sirocco + Bayfidan	114	105
Mixture (Test)	133	72
Mixture (Test)	119	56

- Significantly less than controls (Appendix II)
+ Significantly more than controls
Actual % frequency of control given in brackets
(s) Seed application

TABLE 3.10. Incidence of *F. dimerum* on roots of spring barley (cvs. Golf (G0 and Golden Promise (GP) in relation to fungicide treatment expressed as a percentage of incidence for control plots (averaged for time of assessment and isolation medium).

FUNGICIDE TREATMENT	Bush 87 G	Bush 87 GP	Bush 88 G	Bush 88 GP	Fife 88 G	Fife 88 GP
Control	100(73)	100(62)	100(19)		100(8)	
Ferrax(s)	90					
Ferrax(s) + Patrol	77-	103			450	500
Baytan(s) + Dorin		94				
Dorin			158/211+		350/330	
Sprint			105/147			
Calixin	93	106				
Bayfidan + Corbel		119/121+				
Calixin + (2) Corbel				100/126		463/513
Corbel + Dorin						550
Dorin + Corbel						500
Mon (test)			153	68	350	500
A77114 (test)				121		412
ACF (test)				79		288

- Significantly less than controls (Appendix IV)
+ Significantly more than controls
Actual % frequency of control given in brackets
(s) Seed application

TABLE 3.11. Incidence of *F. dimerum* on roots of winter wheat in relation to fungicide treatment expressed as a percentage of incidence for control plots (averaged for time of assessment and isolation medium).

FUNGICIDE TREATMENT	Fife 87 Avalon	Fife 88 Avalon	Borders 88 Longbow
Control	100(46)	100(25)	100(29)
Sportak alpha + Impact Excel	109		114
Baytan(s) + Sportak alpha + Impact Excel	111	128	114
Baytan(s) + Sportak + Impact excel		84	97
Baytan(s) + Early impact + Impact Excel + Patrol		76	67
Baytan(s) + Citozyme + Sportak alpha + Impact excel			110
Citozyme + Sportak alpha + Impact excel			117
Baytan(s) + Sportak alpha + Bayleton	72		
Baytan(s) + Sportak alpha + ESCA88 F3 (test)		124	
Sportak alpha + ESCA 88 F1 (test)		152	124
Baytan + Dorin + Sportak alpha + Dorin + Bravo + Dorin	96		
Sportak alpha + Sprint		140	124
Sportak alpha + Sportak	93		
Sportak alpha + Impact excel		128	
Sportak + ESCA (test) + Bardew	83		
Sportak alpha + A 696 OC (test)		136	
(2) ESCA (test)	98		
Sportak alpha + (3) Dorin + Bravo + Dorin + Delsene			69
Dorin + Bavistin + Delsene + (2) Dorin + Bravo		116	
(2) N7872 (test)	109		
Hispor + (2) Tilt turbo	98		

- Significantly less than controls (Appendix V)
+ Significantly more than controls
Actual % frequency of control given in brackets
(s) Seed aplication

TABLE 3.12. Incidence of *F. dimerum* on stems of spring barley in relation to fungicide treatment expressed as a percentage of incidence for control plots (averaged for time of assessment and isolation medium).

FUNGICIDE TREATMENT	Bush 87 G	Bush 87 GP	Bush 88 G	Bush 88 GP	Fife 88 G	Fife 88 GP
Control	100(55)	100(43)	100(7)		100(9)	
Ferrax(s)	111					
Ferrax(s) + Patrol	111	107			144	133
Baytan(s) + Dorin		146 +				
Dorin			171/171		88/177	
Sprint			86/86			
Calixin	111	149 +				
Bayfidan + Corbel		126/149 +				
Calixin + (2) Corbel				57/142		**289+**
Corbel + Dorin						256 +
Dorin + Corbel						300 +
Mon (Test)			86	100	77	144 +
A77114 (Test)				100		158
ACF (Test)				71		89

\- Significantly less than controls (Appendix IV)
\+ Significantly more than controls
Actual % frequency of controls given in brackets
(s) Seed application

TABLE 3.13. Incidence of *F. dimerum* on stems of winter wheat in relation to fungicide treatment expressed as a percentage of incidence for control plots (averaged for time of assessment and isolation medium).

FUNGICIDE TREATMENT	Fife 87 Avalon	Fife 88 Avalon	Borders 88 Longbow
Control	100(19)	100(4)	100(3)
Sportak alpha + Impact Excel	189		33
Baytan(s) + Sportak alpha + Impact Excel	158	150	233
Baytan(s) + Sportak + Impact excel		100	167
Baytan(s) + Early impact + Impact Excel + Patrol		150	33
Baytan(s) + Citozyme + Sportak alpha + Impact excel			67
Citozyme + Sportak alpha + Impact excel			67
Baytan(s) + Sportak alpha + Bayleton	168		
Baytan(s) + Sportak alpha + ESCA88 F3 (test)		50	
Sportak alpha + ESCA 88 F1 (test)		100	33
Baytan(s) + Dorin + Sportak alpha + Dorin + Bravo + Dorin	137		
Sportak alpha + Sprint		250	267
Sportak alpha + Sportak	100		
Sportak alpha + Impact excel		200	
Sportak + ESCA (test) + Bardew	126		
Sportak alpha + A 696 OC (test)		25	
(2) ESCA (test)	179		
Sportak alpha + (3) Dorin + Bravo + Dorin + Delsene			33
Dorin + Bavistin + Delsene + (2) Dorin + Bravo		100	
(2) N7872 (test)	142		
Hispor + (2) Tilt turbo	179		

- Significantly less than controls (Appendix V)
+ Significantly more than controls
Actual percentage of control given in brackets
(s) Seed aplication

Other *Fusarium* species :

Species of *Fusarium* other than *F. culmorum* and *F. dimerum* occurred only occasionally at moderate levels or above in trials and the effects of fungicide treatment in these particular cases are presented in Tables (Tables 3.14, 3.15 & 3.16).

On the stems of spring barley in 1987 and on ears in 1988 at the Bush site *F. avenaceum* was generally reduced by fungicide treatment as shown in Table 3.14. There was a variable effect of fungicide treatment on the incidence of stem infection by *F. nivale* at the spring barley trial at Fife in 1988 but here the level of infection on control plots was fairly low (Table 3.15a). However, at the same site high levels of ear infection were substantially reduced by most fungicide treatments. There was also a trend for reduced ear infection of winter wheat at the Fife and Borders sites in 1988 with fungicide treatment (Table 3.15b).

Fungicide treatment had no significant effect on the incidence of *F. poae* infection of stems of winter wheat in 1987 and a variable effect in 1988 at the Fife trials but in 1988 at the Borders site it generally reduced the frequency of this fungus (Table 3.16). The incidence of *F. sambucinum* was not affected by fungicide treatment (Appendices IIIa, IVb, IVc, IVd, IVe, IVf).

Other fungal species :

Generally, fungicide treatment had no significant effect on the incidence of other fungal species with the exception of *Epicoccum* on winter wheat in Fife in 1988 which showed marked increases in response to fungicide treatments (Table 3.17). As may be seen in Appendices IVe & IVd the effects on *Alternaria, Botrytis, Cladosporium* and *Trichothecium roseum* ear colonization were non-significant.

TABLE 3.14. Incidence of *F. avenaceum* at stems (Bush/87) and ears (Bush/88) of spring barley (cvs. Golf (G) and Golden Promise (GP) in relation to fungicide treatment expressed as a percentage of incidence for control plots (averaged for time of assessment and isolation medium).

FUNGICIDE TREATMENT	Stems (Bush/87) G	Stems (Bush/87) GP	Ears (Bush/88) G	Ears (Bush/88) GP
Control	100(5)	100(11)	100(35)	
Ferrax(s)	100			
2/Dorin's			9,3-	
Ferrax(s) + Patrol	120	9-		
Sprint			3,3-	
Baytan(s) + Dorin		27-		
Dorin				
Calixin	20	27-		
Bayfidan + Corbel		27,27-		
Calixin + Corbel				12-
Calixin + 3/Corbels				
Chiltern super six				0-
Corbel + Dorin				
Mon (test)			9-	**50-**
A77114 (Test)				12-
ACF (Test)				29-

- Significantly less than controls (Appendix IV)
+ Significantly more than controls
Actual % frequency of control given in brackets
(s) Seed application

TABLE 3.15. Incidence of *F. nivale* at (a) Fife/88 on stems and ears of spring barley (cvs. Golf (G) and Golden Promise (GP) and (b) Fife and the Borders/88 on winter wheat ears in relation to fungicide treatment expressed as a percentage of incidence for control plots (averaged for time of assessment and isolation medium).

(a) SPRING BARLEY

FUNGICIDE TREATMENT	Stems G	Stems GP	Ears G	Ears GP
Control	100(5)		100(60)	
Sprint				
Ferrax(s) + Patrol	120	340	28$^-$	70
Dorin	6,60		30,3$^-$	
Calixin + Corbel		200		1$^-$
Calixin + (3) Cobel		280		48$^-$
Corbel + Dorin		60,60		0$^-$
Calixin + Corbel + 2 Chiltern super six				76
Mon (test)	0	120	0$^-$	75
A77114 (test)		440		100(71)
ACF (test)		0		11$^-$

(b) WINTER WHEAT (EARS)

FUNGICIDE TREATMENT	Fife 88 Avalon	Borders 88 Longbow
Control	100(53)	100(16)
Baytan(s) + Sportak alpha + Impact Excel	11$^-$	25$^-$
Baytan(s) + Sportak + Impact excel	9$^-$	188$^+$
Baytan(s) + Early impact + Impact Excel	2$^-$	
Baytan(s) + Early impact + Impact Excel + Patrol		19$^-$
Baytan(s) + Citozyme + Sportak alpha Impact excel		6$^-$
Citozyme + Sportak alpha + Impact excel		13$^-$
Baytan(s) + Sportak alpha + ESCA88 F3	8$^-$	
Sportak alpha + ESCA 88 F1 (test)	11$^-$	
Sportak alpha + Sprint+Delsene		19$^-$
Sportak alpha + Sprint	8$^-$	
Sportak alpha + Impact excel	2$^-$	19$^-$
Sportak + ESCA (test)		19$^-$
Sportak alpha + A 696 OC (test)	5$^-$	
Sportak alpha + (3) Dorin		
Bravo + Dorin + Delsene		6$^-$
Dorin + Bavistin + Delsene + Dorin	53$^-$	

- Significantly less than controls (Appendix IV & V)
+ Significantly more than controls
Actual % frequency given in brackets
(s) Seed application

TABLE 3.16. Incidence of *F. poae* on stems of winter wheat in relation to fungicide treatment expressed as a percentage of incidence for control plots (averaged for time of assessment and isolation medium).

FUNGICIDE TREATMENT	**Fife 87 Avalon**	**Fife 88 Avalon**	**Borders 88 Longsbow**
Control	100(8)	100(16)	100(19)
Sportak alpha + Impact Excel	138		32
Baytan(s) + Sportak alpha + Impact Excel	13	69	16
Baytan(s) + Sportak + Impact excel		125	42
Baytan(s) + Early impact + Impact Excel + Patrol		113	63
Baytan(s) + Citozyme + Sportak alpha Impact excel			68
Citozyme + Sportak alpha + Impact excel			74
Baytan(s) + Sportak alpha + Bayleton	50		
Baytan(s) + Sportak alpha + ESCA88 F3 (test)		100	
Sportak alpha + ESCA 88 F1 (test)		19	37
Baytan(s) + Dorin + Sportak alpha + Dorin + Bravo + Dorin	150		
Sportak alpha + Sprint		63	47
Sportak alpha + Sportak	38		
Sportak alpha + Impact excel		38	
Sportak + ESCA (test) + Bardew	75		
Sportak alpha + A 696 OC (test)		94	
(2) ESCA (test)	150		
Sportak alpha + (3) Dorin + Bravo + Dorin + Delsene			47
Dorin + Bavistin + Delsene + (2) Dorin+ Bravo		119	
(2) N7872 (test)	163		
(2) Hispor + Tilt turbo	25		

- Significantly less than controls (Appendix V)
+ Significantly more than controls
Actual % frequency of control given in brackets
(s) Seed application

-

TABLE 3.17. Incidence of *Epicoccum* (Borders) on ears of winter wheat in relation to fungicide treatment expressed as a percentage of incidence for control plots (averaged for time of assessment).

FUNGICIDE TREATMENT	Borders 88
Control	100(6)
Baytan(s) + Sportak alpha + Impact Excel	883
Baytan(s) + Sportak + Impact excel	533
Baytan(s) + Early impact + Impact Excel + Patrol	350
Baytan(s) + Citozyme + Sportak alpha Impact excel	567
Citozyme + Sportak alpha + Impact excel	800
Sportak alpha + Sprint+Delsene	467
Sportak alpha + Impact excel	817
Sportak + ESCA (test)	850
Sportak alpha + (3) Dorin Bravo + Dorin + Delsene	700

- Significantly less than controls (Appendix V)
+ Significantly more than controls
Actual % frequency of control given in brackets
(s) Seed application

3.3.2 Laboratory tests on the fungicide sensitivity of different *Fusarium* species.

The results of colony growth assessments for the ten species of fungi are given in Table 3.18 which gives ED_{50} values and the minimum triadimenol concentration causing complete inhibition of mycelial growth with respect to the fungicides Dorin and Baytan. It may be seen that Dorin showed a greater inhibitory effect on *F. dimerum* and *F. nivale* than on the other tested *Fusarium* species, *viz F. avenaceum, F. culmorum, F. graminearum, F. moniliforme, F. sambucinum* and *F. sulphureum*. Thus the triadimenol concentrations (ug/ml) to give inhibition of colony growth was 25.0 for *F. dimerum* and *F. nivale* whereas other species still showed some growth at a concentration of 980.

In comparing responses to Baytan *F. nivale* and *F. dimerum* were again found to be more sensitive than other species, both failing to grow at a concentration of 25.0 ug/ml. *F. avenaceum, F. culmorum, F. graminearum, F. moniliforme, F. poae* and *F. sambucinum* all showed some growth at 50 ug/ml but none grew at 980 ug/ml.

F. nivale seemed to be extremely sensitive to both fungicides and *F. dimerum* apparently seemed rather less sensitive to Baytan than to Dorin.

When testing different isolates of *F. nivale* it was observed that they exhibited a similar degree of sensitivity in response to Dorin and to Baytan. As in the inter-specific tests the different isolates were all more sensitive to Dorin than to Baytan. It might be noted that one of the isolates (Ni2 isolated from roots of winter wheat

TABLE 3.18. Response of different fungal species to Dorin and Baytan fungicides expressed as dosage rate of triadimenol (ug/ml).

FUNGAL SPECIES	DORIN ED_{50} SED (df=) ± 6.1	DORIN MINIMUM INHIBITORY CONCENTRATION	BAYTAN ED_{50} SED (df=) ± 6.1	BAYTAN MINIMUM INHIBITORY CONCENTRATION
F. avenaceum	54	>980	62	50
F. culmorum	67	>980	64	50
F. dimerum	28	25	44	25
F. graminearum	65	>980	72	50
F. moniliforme	42	>980	46	50
F. nivale	20	25	30	25
F. poae	47	>980	60	50
F. sambucinum	53	>980	48	50
F. sulphureum	51	>980	39	50
T. roseum	39	>980	59	50

TABLE 3.19. Distribution frequency of isolates grouped according to ED_{50} values (triadimenol ug/ml).

FUNGAL SPECIES	FUNGICIDE	ED_{50} GROUPING 1-10	11-20	21-30	31-40	41-50	51-60	61-70	>70
F. culmorum (29)	Baytan	0	0	0	0	2	8	11	8
F. nivale (8)	Baytan	0	0	1	6	1	0	0	0
F. nivale (8)	Dorin	0	8	0	0	0	0	0	0

Number of isolates given in brackets

at Bush, 1988) showed a somewhat greater sensitivity to both fungicides than the remaining isolates.

Table 3.19 also shows the range of response of 29 different isolates of *F. culmorum* to Baytan. In comparison with *F. nivale* there was a greater variation tolerance but a greater range of among isolates of *F. culmorum*. Colony growth of isolate Cu1 (isolated from ears of spring Barley at Bush, 1988) was unusual in showing a reduction at the lower rate of fungicide although it tended to behave in a similar way to other isolates at higher concentrations. Isolates Cu7, Cu13, Cu20, Cu21 and Cu22 (isolated from roots of spring barley at the Borders, ears of winter wheat at Fife, ears of spring barley at Bush 1987, roots of spring barley at the Borders, respectively) all seemed to be more sensitive to Baytan.

3.4 DISCUSSION

In assessing the effect of fungicide treatment on the incidence of the more prevalent species of *Fusarium*, there was an overall tendency for chemical applications, aimed primarily at the control of other pathogens, to give some reduction in the incidence of the major pathogenic *Fusarium* species, *F. culmorum*. In an attempt to indicate fungicide groups which gave the greatest reductions, Table 3.20 gives the particular grouping which reduced incidence in particular trials to at least 20% of that from untreated plots. It may be seen that the fungicides which figure frequently in giving greater disease control levels include triazoles, morpholines, benzimidazoles and, in cases where they were applied, phthalimides and imidazoles. These observations are partly in keeping with reports from other workers who have indicated disease control with triazoles and

TABLE 3.20. Commercial fungicide treatments (based on chemical grouping) giving a reduction of incidence of *Fusarium culmorum* isolated from parts to 20 per cent or less of incidence from untreated control plots from different trials.

(a) ROOTS

FUNGICIDE	WINTER BARLEY		SPRING BARLEY									WINTER WHEAT								
TREATMENT	BU/87		BU/87					/88	BO/88			FI/88								
Triazole	+	+	+	+	+		+	+	+		+	+	+		+	+	+	+	+	+
Morpholine	+	+		+	+	+	+	+	+	+	+			+	+	+				+
MBC		+	+	+	+				+				+	+		+	+		+	+
Dithiocarbamate		+														+				+
Amino pyrimidine			+	+					+											
Phthalimide												+	+		+		+	+	+	+
Imidazole													+	+	+		+		+	
Chlorothalonile																+				+

(b) STEMS (c) EARS

	WINTER WHEAT				WINTER WHEAT				WINTER WHEAT					
	stems				FI/88			BO/88	BO/88					
Triazole	+	+			+		+	+	+	+	+	+	+	+
Morpholine		+	+	+		+		+						+
MBC			+		+	+	+	+		+		+	+	+
Dithiocarbamate			+					+						+
Dicarboximide				+										
Imidazole					+	+	+	+				+	+	+
Phthalimide					+		+		+	+		+	+	
Chlorothalonile								+		+	+			+

benzimidazoles (Wainwright *et al.*, 1979) and sometimes with prochloraz (an imidazole) (Jenkins *et al.*, 1988). However, in summarizing the recent position regarding the control of *Fusarium* with fungicidal sprays, Jenkins *et al.* (1988) comment that there is no substantial evidence that sprays as currently used give an effective and consistent control. Moreover, since significant levels of disease tend to be erratic, outbreaks cannot be forecast and it would seem that sprays cannot be applied in time to be effective. Nevertheless, from the results of the present work there is evidence that sprays used mainly to control leaf diseases and eyespot can have an incidental but beneficial effect in giving some reduction in *Fusarium* infection. This is shown not only in results for *F. culmorum* but also with other pathogenic species, namely *F. avenaceum* and *F. nivale*. From this evidence one might infer that the general survey results (Section 2) show lower frequencies of pathogenic *Fusarium* species than would occur on untreated cereal plots. However, fungicides are now widely used commercially to control cereal leaf diseases and eyespot (Jenkyn & Plumb, 1981) and the survey results reported here are probably reasonably in line with the general field position.

One interesting aspect of the results is the reduced incidence of root infection for *F. culmorum* from fungicide applications. Most of the treatments were in the form of sprays and although the chemicals used were mainly systemic, they are not phloem-translocated and would not, therefore, be carried through the plant to the roots. Since roots were sampled from near the stem base, it is also possible that the presence of fungicide in the lower part of the shoot had an effect in restricting crown and further root infection as it was assessed. It is possible that some spray deposition on the soil may have had some effect, but this would not be expected to be substantial. Moreover, *F. dimerum* was not reduced to any general extent on roots: its superficial form of association would be expected to expose it more to at least triazole fungicides. Another explanation to account for the control of root infection may relate to the chemical control of shoot diseases rendering roots less prone to infection by *Fusarium*.

With regard to non-pathogenic *Fusarium* species, represented mainly by *F. dimerum*, this species was usually unaffected by fungicide treatments. This might be explained by the superficial form of colonization and the systemic nature of most of the chemicals used. In a few cases where fungicide treatment increased the incidence of *F. dimerum* it is possible that fungicide control of pathogens allowed a less competitive environment for this organism at the plant surface. This might also explain the response of *Epicoccum* to fungicide treatment in one instance: non-pathogenic fungi as a whole were generally not affected by fungicide treatment but the marked increase in *Epicoccum* on ears of winter wheat (Fife, 1988) might be attributable to reduced populations of competitive, parasitic organisms.

The *in vitro* tests of the response of different *Fusarium* species to Baytan and Dorin, two fungicide mixture formulations used widely as a seed treatment and spray respectively, showed that while organisms tested were suppressed, *F. nivale* and *F. dimerum* were more sensitive than other species. *F. nivale* and *F. dimerum* showed a similar pattern of response to fungicides while *F. avenaceum, F. culmorum*, *F. graminearum, F. moniliforme, F. sambucinum, F. sulphureum* and *Trichothecium roseum* showed a further grouping in their response. This may be associated with the taxonomic relationship of the various fungi, *F. nivale* and *F. dimerum* belonging to the Arachnites group and most others to the Discolor Section (Booth, 1971), suggesting differences in metabolic systems characterizing different groups.

The greater sensitivity of *F. nivale* compared with *F. culmorum* may account for the apparent decline in incidence of *F. nivale* in recent years, from a comparison of literature records and referred to in Section 2(Foister, 1961; Noble, 1970; Hewett, 1983; Rennie, & Richardson, 1983). The extensive use of fungicides in the last decade may have selected against this fungus and account for the dominance of the less sensitive *F. culmorum* in the present survey. While *F. dimerum* was also relatively susceptible to fungicide from the present tests it may be noted that it is a superficial colonizer of cereals and would thus not be exposed to the systemic fungicides to the same extent as *F. nivale*.

In comparing the response of the less sensitive species of *Fusarium*, Baytan appeared to be slightly more toxic than Dorin suggesting that the MBC component in the former may have been more effective than morpholine in Dorin. However, with *F. nivale* and *F. dimerum* the reverse effect was the case, again suggesting a distinctive metabolic system for these fungi.

The assessed intra-specific variation in sensitivity of *F. nivale* and *F. culmorum* to the two fungicides showed that all *F. nivale* isolates were highly sensitive with very little differences between isolates. However, with *F. culmorum* there was a greater range of variation between isolates suggesting a degree of tolerance in certain cases. This may point to a risk of the emergence of fungicide insensitivity in populations of this species. Thus although the widespread use of fungicides in cereal crops might account for a lower general incidence of *Fusarium*, it may be predisposing towards fungicide insensitivity problems in some species.

SECTION 4
THE EFFECT OF EAR INOCULATION OF CEREALS WITH DIFFERENT FUNGAL SPECIES ON GRAIN DEVELOPMENT

4.1 INTRODUCTION

The experimental work in this section is concerned primarily with the effects on grain development of ear inoculation with *Fusarium* species with particular reference to those species identified in the survey of field trials, including those reported as weak parasites associated with cereal inflorescences. An assessment of host crop cultivar response to the fungi concerned was also considered. In two of the studies inoculation with *Trichothecium roseum*, a species sometimes occurring frequently on ears in the survey, was included in the experimental treatments in order to determine any pathogenic effects of this fungus and its interaction with other fungi.

Head blight or scab of cereals is a destructive disease in the temperate, humid and semi-humid areas of the world where maize, wheat and barley are the main cereal crops grown. Various *Fusarium* species have been reported as the main cause of scab including *F. graminearum, F. culmorum, F. avenaceum, F. nivale* and *F. poae*. Which of those may dominate in the different parts of the world seems to be related to temperature and humidity. *F. graminearum* is the main species on cereals in the warmer regions such as the Corn Belt states of the USA, California (Oswald, 1949; 1950), México and Michoacán states in México (Ireta, 1986), eastern Australia (Burgess *et al.* 1975), southern Europe (Cassini, 1981), and the lower reaches of the Yangtze area of the People's Republic of China (Kelman & Cook, 1977). *F. culmorum* seems to be the main pathogen of cereals in the Prairi and Maritime Provinces of Canada, in the northern and central Great Plains and Northwest states of the USA and in Great Britain, Holland and Germany (Cook, 1981). *F. avenaceum* and *F. nivale* seem to share the main distribution in areas such as the Pu get Sound area of the Northwest and adjacent parts of Canada, the panhandle of Idaho and adjacent eastern Washington (Cook, 1968), eastern Canada, Victoria, Australia, Scotland and other areas characterized by cool climates during the main growing season (Cook, 1981b).

The first sign of blight infection produced by *F. culmorum*, *F. avenaceum* and *F. graminearum* is a slightly brown and water-soaked spot, 2 to 3mm in length, on the glumes. The veins appear more water-soaked and have a much darker olive-green appearance than the area between them. The points at which the infected glume or glumes are attached to the rachis soon show a water-soaked appearance too. The affected area increases more or less rapidly, depending on weather conditions, until the whole spikelet is covered and infection spreads to neighbouring spikelets. Infection of the rachis causes blighting or dying of the whole head above the point of infection. In such cases the dead spikelets shrink and become more closely adpressed to the rachis, while the uninfected portions of the head continue their normal development to maturity. The point of infection may be covered with a short, cottony or slightly pinkish fungal growth, which extends further over the infected area and a layer of conidia develop if the weather is favourable. The masses of conidia tend to be more dense in the cases of infection produced by *F. culmorum* and *F. avenaceum* than by *F. graminearum*: with *F. graminearum* blue-dark perithecia are often observed. Although *F. nivale* has often been isolated from bleached spikelets in the UK and regarded as the main seed-borne *Fusarium* species, its symptoms are not well characterized: in some reports they are described as usually inconspicuous (Hewett, 1983) whereas in others (Rapilly, Lemaire & Cassini, 1973; Fehrmann, 1988) the fungus is said to produce a brown glume spot with a dark brown margin. *F. poae* although regarded as a saprophyte or at most a weak parasite, seems to be able to colonize wheat and barley spikes at any ear development stage with glume spots very similar to those produced by *F. nivale* and *Botrytis* *cinerea*. This fungus, however, does not affect seedling emergence.

Grains infected by *F. graminearum* are described by (Dickson, 1947) as more or less shrivelled with a scabby appearance due to tufty mycelial outgrowths from the seed coat and white, pink or light brown in colour depending on the time of infection and the prevailing weather. Grains infected with *F. culmorum* may also be shrivelled but the fungus rarely penetrates as far as the embryo. Millar & Colhoun (1969a) found grains naturally infected by *F. nivale* to be shrivelled with grey-brown patches around the embryos without any reduction in the germination rate. Bateman (1983) isolated this fungus from the seed coat, endosperm and embryo but infections were concentrated in the space beneath the epidermis and in the crease of wheat grains.

Many factors seem to be involved in head blight development. Ascospores and/or macroconidia released at the time of anthesis (anthers production) and a high humidity (92 to 100% rh) seem to be needed to produce head blight. Symptoms may appear in 7 days in wheat kept moist for 18 h after inoculation, but in only 3 days in wheat kept wet continuously. If the inoculum arrives before or after anthesis, infections may still occur but the seriousness of the disease is greatly reduced (Sutton, 1982). Both ascospores and conidia play a part in the spread of the disease but there is little evidence available on the sources or dispersal mechanisms of the inoculum. In the UK, *F. nivale* can spread through the dispersal of ascospores produced in perithecia on leaf sheaths but there is very little information on the dissemination of conidia or on the means of spread of other *Fusarium* pathogens such as *F. culmorum* and *F. avenaceum*.

Pugh, Johann & Dickson (1933) reported that ear infections by *F. graminearum* occurred at flowering time, or shortly after, rather than earlier, because of the presence of anthers on which the fungus first developed as a saprophyte and from which it spread to the interior of the flower, especially to the developing kernel. Similar results were obtained by Anderson (1948) who inoculated wheat heads at partial anthesis and found that only those spikelets that had produced anthers became infected. Wheat spikes apparently are not receptive to this pathogen prior to anthesis, but are receptive in the period from flowering to the soft dough stage. The stage of peak receptivity differs among cultivars.

Later studies have shown that some compounds produced by cereal plants are responsible for this higher susceptibility of plants to *Fusarium* ear infection at the time of anthesis. Strange & Smith (1971a) obtained convincing evidence that the anthers promote infection of wheat spikes when they inoculated suspensions of macroconidia or ascospores to normal spikelets in which the anthers were removed. Emasculated spikelets rarely became infected compared with the non-emasculated plants which were heavily infected. Massive growth of growth of *F. graminearum* occurred on young anthers that had not shed pollen (Strange & Smith, 1971b). Powerful stimulants of *F. graminearum* have been recovered from wheat anthers and pollen and were identified as the quaternary ammonium compounds choline and betaine (Strange, Majer & Smith, 1974). These substances failed to stimulate germination of macroconidia of *F. graminearum, F. culmorum* and *F. avenaceum* but enhanced hyphal growth of those fungi soon after germination (Strange & Smith, 1978a; 1978b) which explains the close relationship between flowering and infection (Strange & Smith, 1970; Naik and Busch, 1978). *F. nivale*, which according to Strange & Smith (1978a) is not a cause of ear disease, was not stimulated by either choline or betaine extracted from wheat-germ. In the case of *F. graminearum*, the same workers found that betaine and choline are the most important stimulatory compounds but that different ones are also involved in the stimulation of mycelial growth of *F. avenaceum* and *F. culmorum*.

Although *F. graminearum* may infect the spikes after intensively colonizing the anthers, it may also invade the spikes by other routes. Direct infection by macroconidia or ascospores seem to be unusual, though Schroeder & Christensen (1963) have concluded that the infection occurs whenever the fungus comes in contact with the spikelets or rachis. Ireta (1986) successfully inoculated spikelets of wheat by wounding the tissues and then inoculating the fungus with wet cotton. This seems to suggest that natural infections could occur through wounds made by insects, birds or other agents with possible enhancement by nutriment sources as frass or honeydew.

Evidence obtained by several workers (Mesterhazy & Rowaished, 1977; Sturz & Johnston, 1983; Mathis, Forrer & Hessler, 1986) suggests that precolonization of spikes and other aerial parts by other fungi such as *Erysiphe graminis*, *F. poae* and *F. avenaceum* may predispose cereal plants to ear infection by *F. graminearum* and *F. culmorum*. On the other hand, Bateman (1979) found that *F. nivale* was prevented from infecting cereal plants by saprophytic microorganisms such as *Alternaria* and *Epicoccum*, during seed germination and early seedling growth and also during seed colonization.

The aim of these experiments was to evaluate the pathogenicity of different *Fusarium* species in relation to time of inoculation.

The experiments are considered under three headings as follow:-

(a) The effects of ear inoculation with different *Fusarium* species at different growth stages on grain development in cultivars of barley, oats and wheat;

(b) The effect of *Fusarium* and *Trichothecium roseum* ear inoculation at different growth stages on grain development in cultivars of barley, oats and wheat;

(c) The effects of *Fusarium* and *Trichothecium roseum* ear inoculation at different growth stages on grain development in two cultivars of barley.

The subsequent effects of these inoculation treatments on seed germination and seedling growth are considered in the next section.

4.2. MATERIALS AND METHODS

Over the period 1987 to 1989 a series of three glasshouse experiments were carried out to assess the pathogenicity of different *Fusarium* species towards cereals following ear inoculation. In the second and third experiments *Trichothecium roseum* inoculation treatments were also included.

4.2.1 EXPERIMENT 1.

Seed of cultivars of barley (Golden Promise), oats (Trafalgar and Leanda) and wheat (Club and Dollar) were obtained from the Official Seed Testing Station at

East Craigs. Pots sown with barley, oats or wheat were placed inside a glasshouse equipped with an automatic irrigation system and arranged in a split-plot design with a randomized block lay-out. Cultivars and species of fungi were assigned to the main plots and time of inoculation to a sub-plot. Four replicates were used. Each sub-plot comprised a pot (18 cm diameter) sown with five seeds. The *Fusarium* cultures were grown on PSA (potato-sucrose-agar) or PDA and incubated for about 21 days at 20^{o}C with near-ultraviolet light to stimulate sporulation. In the case of *F. nivale*, the temperature was reduced to 10^{o}C due to its different temperature requirement.

In preparing inoculum, 10-20 ml of distilled water was added to each plate and the fungal growth scraped from the agar. The resultant spore suspension was then filtered through four layers of gauze and the number of spores/ml of solution determined using a haemocytometer. The concentration of spores in the suspension was the adjusted with distilled water to 500,000 spores/ml. The fungi *(F. avenaceum, F. culmorum, F. graminearum, F. nivale* and *F. poae)* used for inoculation were obtained from the Commonwealth Mycological Institute. Three different inoculation dates were employed depending on the development of the plants. The first inoculation was made on August 17, and the second and third inoculation were made 10 and 20 days later. The growth stages at the first inoculation were GS 65 for both cvs. of wheat, and 70 for the oat and barley cvs. At the time of each inoculation five heads per pot, were selected and labelled to indicate the respective growth stages at inoculation, which were the beginning of anthesis, anthesis half-way and anthesis complete according to the classification of Zadoks, Chang & Konzak (1974) and modified by Tottman, Makepeace & Broad (1979).

Approximately 1 ml of inoculum was applied with a Humbrol spray gun to five cereal inflorescences at the appropriate growth stage in each individual pot under the cover of a polythene bag which was used to avoid contamination and keep to a high humidity. Bags were left over the inflorescences for 8 days. Controls in the experiment were set up by using distilled water containing no inoculum.

At maturity, the seeds from labelled heads were harvested by hand and threshed in lots according to the different treatments. Seeds were counted and weighed after drying at room temperature and the thousand seed weight was calculated for each lot.

4.2.2 EXPERIMENT 2.

This second experiment concerning ear inoculation of different cereal crops at different growth stages was carried out following more or less the same procedures as in the first one but two more fungi were included and some of the cultivars changed. In this experiment, the cultivars Golden Promise and Golf (barley), Leanda and Rollo (oats), and Dollar and Tonic (wheat) were sown in 18 cm pots in a glasshouse on 12 **April** 1988. The fungi for inoculation were *F. avenaceum, F. culmorum, F. graminearum, F. nivale, F. poae, F. sambucinum and T. roseum*, using isolates from the fungicide field trials in 1987. The three dates of inoculation were carried out on 12, 19 and 26 July 1988 when the cereal plants were at growth stages between GS 60 and 65 for the first inoculation date. The experimental design was in the form of a split-plot with fungal inoculum treatments as main plots, and cultivar and time of inoculation forming sub-plots in a randomized block layout with four replicates. Harvesting, threshing and counting of grains per ear were done manually when the plants were fully ripened, and grain weight determined after drying.

4.2.3 EXPERIMENT 3.

The aim of this last experiment was to investigate the effect of *T. roseum* as colonizer of ears either one week before or after the inoculation of the *Fusarium* species used in Experiment 2.

Two cultivars of barley, Camargue and Sherpa, were sown in 18 cm pots in the plant growth unit of the Edinburgh School of Agriculture on January 5 1989. Six species of *Fusarium* and *T. roseum* isolated from the 1988 field trials were inoculated at three different growth stages during ear development. One week before or after the inoculation of those fungi, ears were sprayed with a suspension of 500,000 spores/ml of *T. roseum* or left unsprayed. As in previous experiments plants were covered with a plastic bag to preserve humidity and avoid cross contamination. The experiment was arranged in a randomized block design with two replicates, cultivar and inoculation date forming main plots and sub-plots respectively, while *T. roseum* treatment formed sub-sub-plots and fungal species used for inoculation randomized within these. At maturity, plants were harvested manually and placed in paper bags for drying at room temperature: number and weight of grains per five ears were recorded and the 1000 grain weight was calculated.

Harvested seeds from the three experiments were used for seed health and germination tests referred to in the next section.

4.3. RESULTS

4.3.1 EXPERIMENT 1. The effects of ear inoculation at different growth stages with different *Fusarium* species on grain development in cultivars of barley, oats and wheat.

From visual examination following inoculation treatment it was observed that both cultivars of wheat were heavily colonized by *F. culmorum* (Plate 4.1 and 4.2) and to a lesser extent by *F. graminearum* (Plate 4.3) and *F. avenaceum* (Plate 4.4). *F. poae* and *F. nivale* did not produce any symptom. Both oat cultivars and the barley, Golden Promise, were also seen to be colonized by *F. culmorum*, *F. graminearum* and *F. avenaceum* but not as much as wheat.

Statistically significant differences in the number and weight of grains produced and in grain size were associated with the effects of cultivar and date of inoculation but significant interactions between cultivar and date of inoculation were found (Appendix VIa to VIc). Inoculation with different species of *Fusarium* significantly affected grain weight yield and grain size but did not affect grain number.

From Figure 4.1 it may be seen that the two oat cultivars, Leanda and Trafalgar, yielded a greater number and weight of grain than the other cereal cultivars but the two wheat cultivars, Club and Dollar produced heavier grains than the remaining cultivars. The barley cultivar Golden Promise gave the smallest number of grains, yield and grain size.

While the fungal inoculation overall had no effect on grain number, *F. graminearum, avenaceum* and *F. culmorum* produced a significantly lower grain weight than the control (Figure 4.2), and *F. graminearum* and, especially, *F.*

FIGURE 4.1. Grain number and weight in relation to cereal species and cultivar (averaged for fungal inoculation treatment). Glasshouse experiment–1987.

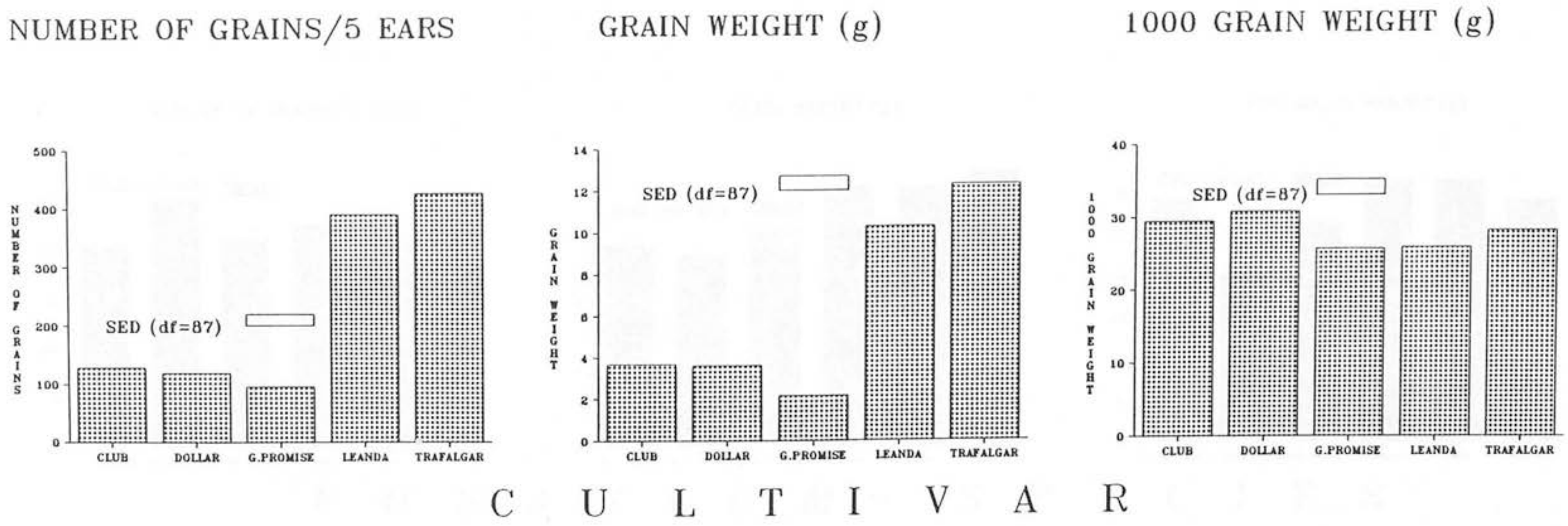
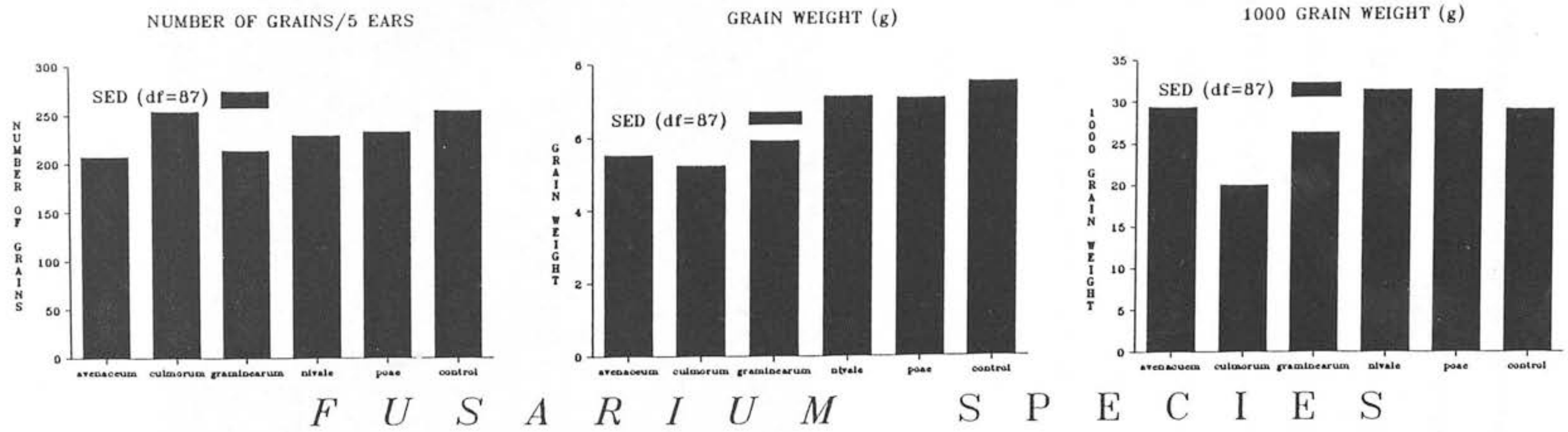


FIGURE 4.2. Effect of ear inoculation with different *Fusarium* species on grain number and weight (averaged for host cultivar and time of inoculation). Glasshouse experiment–1987.



culmorum produced significantly smaller grain compared with the control. *F. nivale* and *F. poae* inoculation had no significant effect on grain development.

The earliest inoculation (beginning of anthesis) gave a significantly lower grain number and weight than later inoculations, while grain size was lower from the first two inoculation dates compared with the last (Figure 4.3). However, in considering the interaction between cultivar and time of inoculation (Figure 4.4), it was found that the time of inoculation had little effect on the grain number and weight of the barley cultivar Golden Promise, whereas with the other cereal cultivars grain number and weight were reduced from early inoculations. With respect to grain size the oat cultivars and barley gave lower values from the first inoculation than from later ones but wheat cultivars tended to give relatively high 1000 grain weights from the first inoculation date (Figure 4.4).

PLATE 4.1. *Fusarium culmorum* colonization of ears of wheat (cv. Club) 10 days after inoculation.

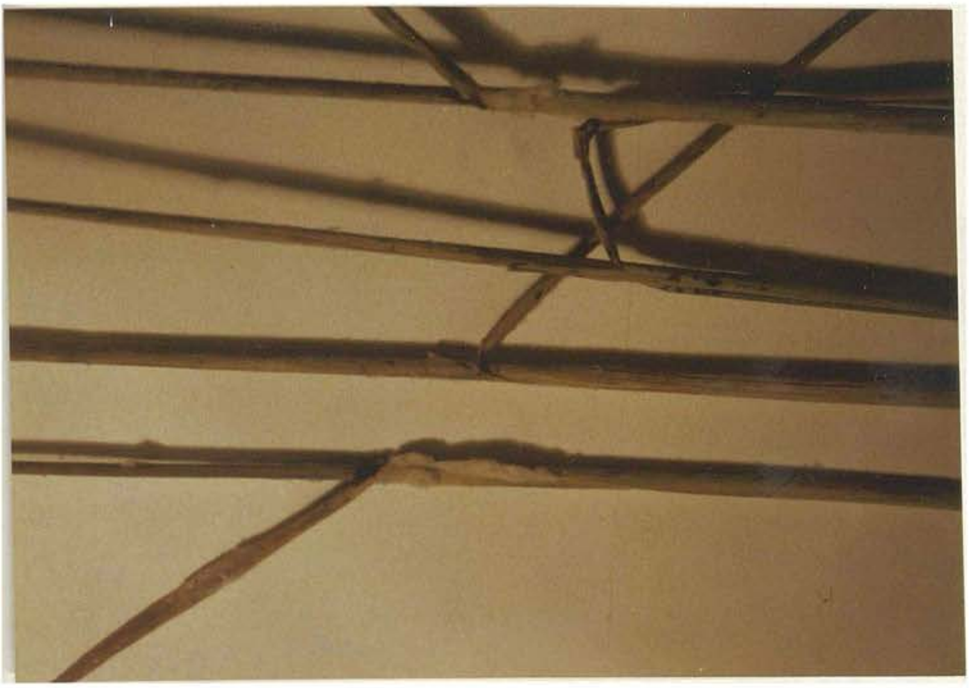


PLATE 4.2. *Fusarium culmorum* colonization of upper leaves and stems of wheat (cv. Club) at plant maturity.

PLATE 4.3. *Fusarium graminearum* colonization of ears of wheat (cv. Club) 10 days after inoculation.

FIGURE 4.3 Effect of time of inoculation on grain number and weight (averaged for cultivar and *Fusarium* inoculum treatment). Glasshouse experiment–1987.

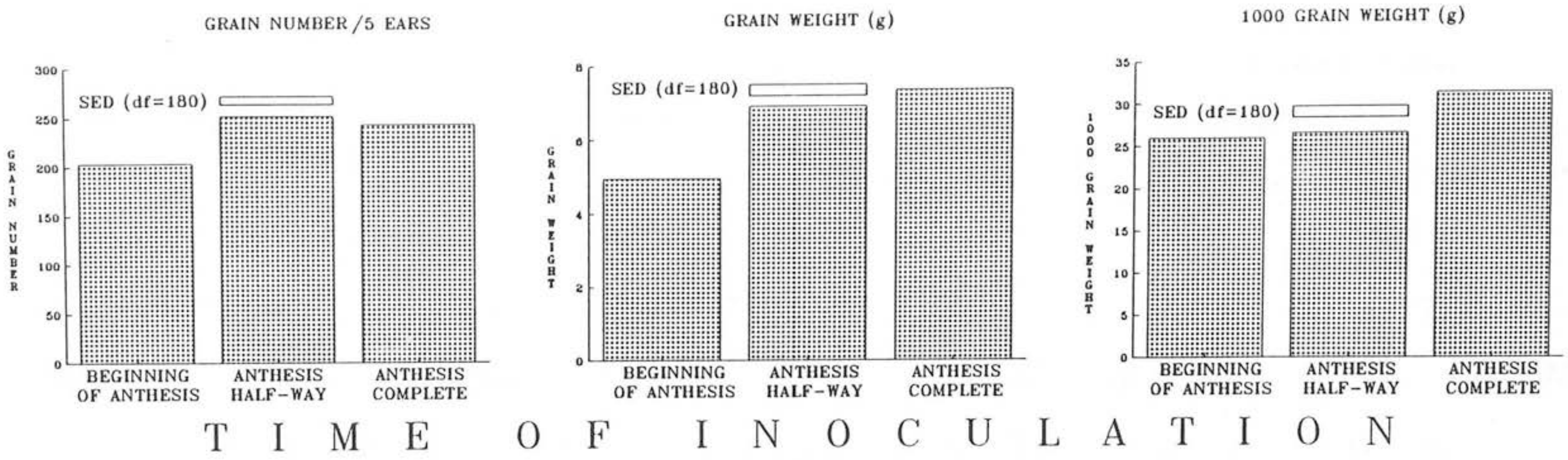


FIGURE 4.4 Grain number and weight in relation to cultivar and time of inoculation (averaged for *Fusarium* species). Glasshouse experiment–1987.

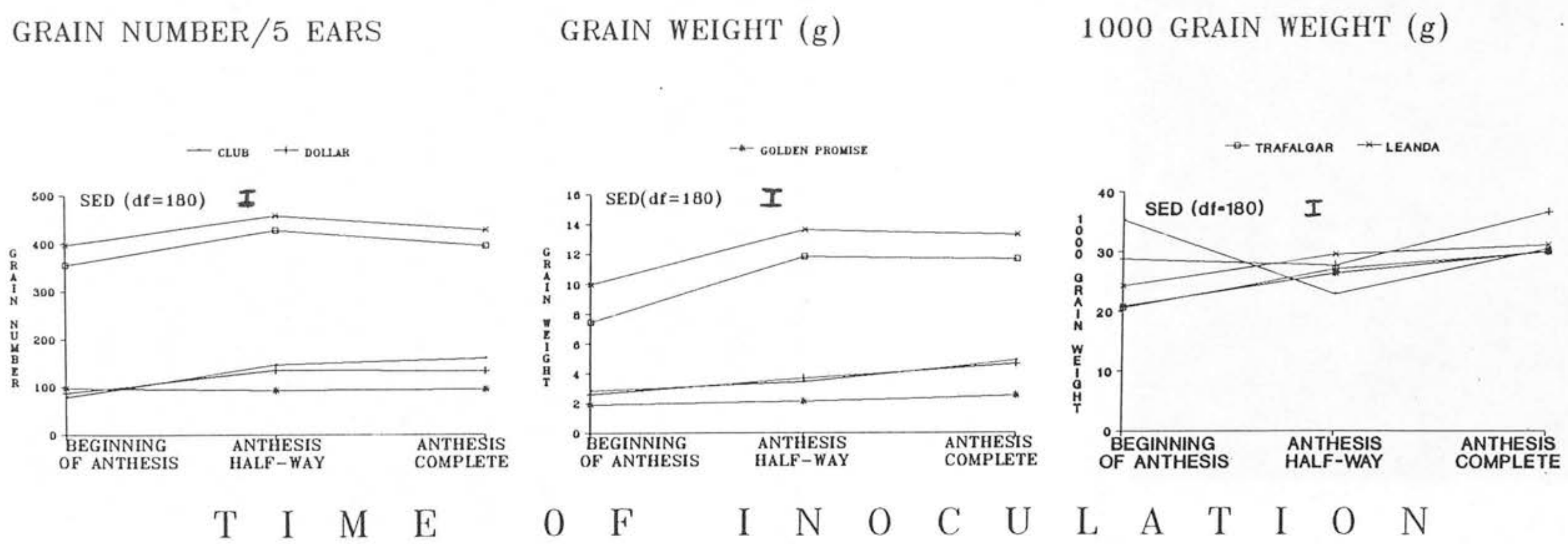


PLATE 4.4. *Fusarium avenaceum* colonization of ears of wheat (cv. Club) 10 days after inoculation.

4.3.2 EXPERIMENT 2. The effects of *Fusarium* and *Trichothecium roseum* ear inoculation at different growth stages on grain development in cultivars of barley, oats and wheat.

The analyses of variance for the effects of cultivar, fungal inoculum treatment and time of inoculation on grain number, weight yield and 1000 grain weight are given in Appendices VIIa to VIIc. The main effects of these three factors are illustrated in Figures 4.5 to 4.7. Grain numbers and weight per five ears were significally higher for the two oat cultivars than for the other cereals but no differences were evidenced for 1000 grain weight (Figure 4.5). In comparison with water, fungal inoculation generally reduced grain number and size and, in the case of grain weight and grain size, the reduction was greater with *F. avenaceum*, *F. graminearum* and particularly *F. culmorum* (Figure 4.6). From

FIGURE 4.5 Grain number and weight in relation to cereal species and cultivar (averaged for *Fusarium* inoculation treatment). Glasshouse experiment 1988.

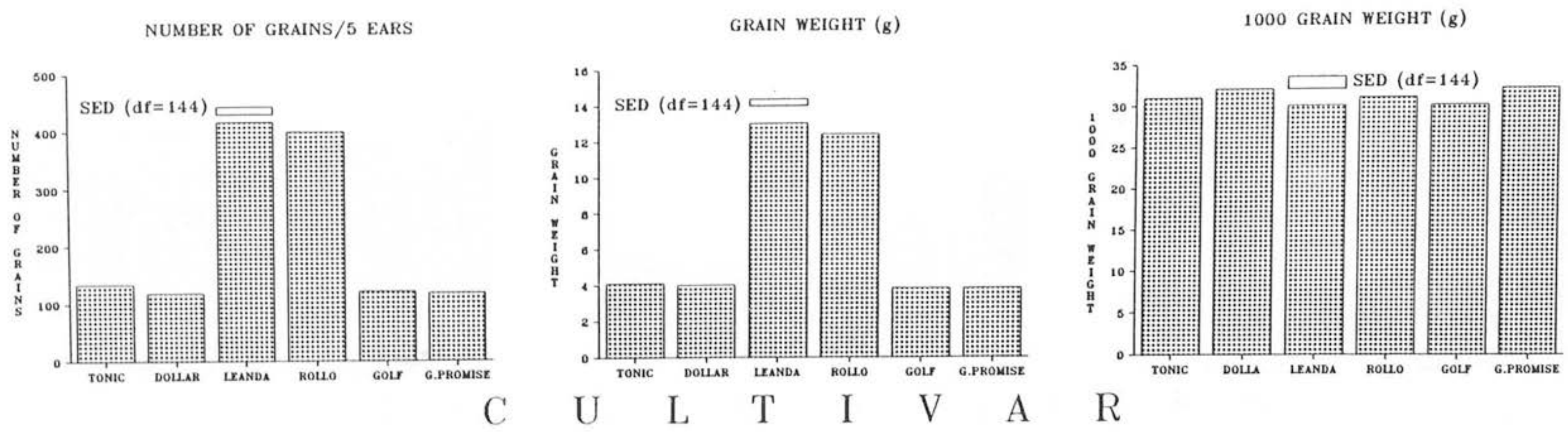


FIGURE 4.6. Effect of ear inoculation with different fungal species on grain number and weight (averaged for host cultivar and time of inoculation). Glass-house experiment-1988.

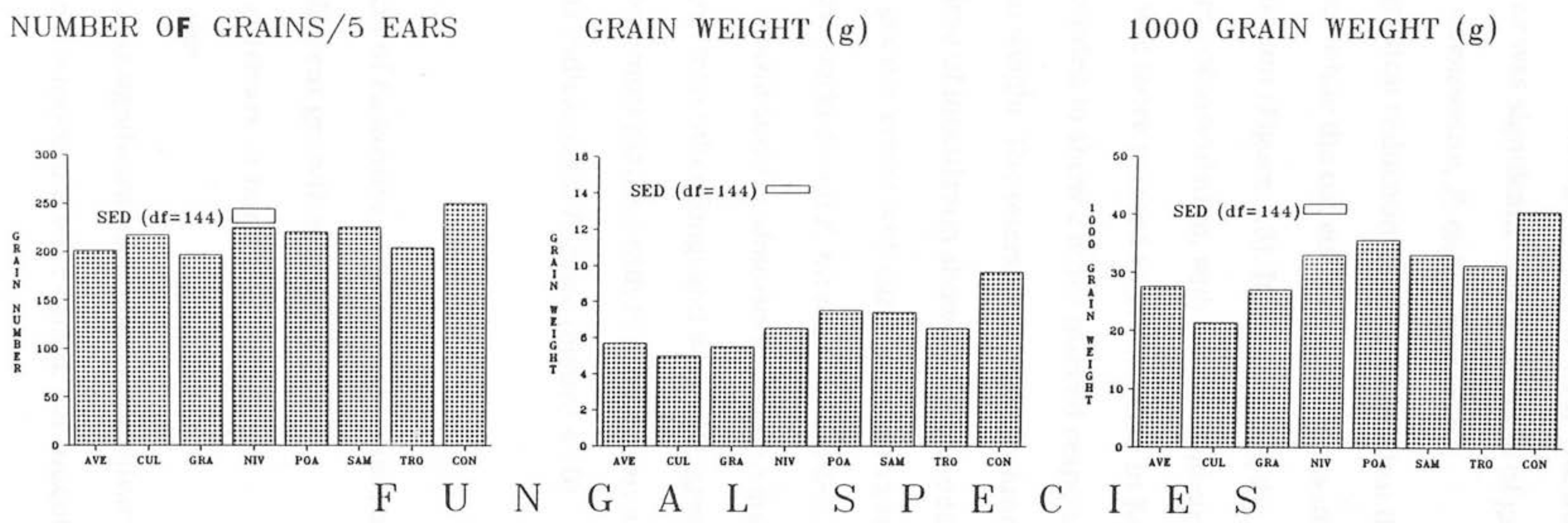


Figure 4.7 it is seen that grain numbers, weight and size progressively decreased with earlier time of inoculation. There were, however, significant interactions between these various factors as illustrated in Figures 4.8 to 4.10. The interaction between inoculum used and cultivar was significant only in the case of grain weight yield. In all three cereals *F. avenaceum, F. culmorum* and *F. graminearum* tended to give the greatest reduction in grain weight but the effect seemed rather more marked in oats, while the oat cultivar Leanda was unusual in giving a low grain weight with *T. roseum* (Figure 4.8). In considering the interaction between cultivar and time of inoculation, with the oat cultivars the adverse effect of early inoculation was more marked in Leanda than in Rollo (Figure 4.9). Barley cultivars also tended to show a more marked response to early inoculation for the 1000 grain weight. The interaction between fungal species used for inoculation and time of inoculation showed that all species tended to reduce grain number to greater extent with early inoculation relative to the controls, but this effect was most marked with *F. nivale* and *F. culmorum* (Figure 4.10). With grain weight *F. nivale* and *F. culmorum* tended to give a greater response to early inoculation than other fungi and with 1000 grain weight the response to early inoculation was most marked with *F. avenaceum* while no response to time of inoculation was indicated for *F. poae* (Figure 4.10).

4.3.3 EXPERIMENT 3. The effects of *Fusarium* and *Trichothecium roseum* ear inoculation at different growth stages on grain development in two cultivars of barley.

In the 1989 glasshouse experiment, no significant main effects of cultivar, time of inoculation, or adding *T. roseum* to the inoculum were found. Ear inoculation

FIGURE 4.7 Effect of time of inoculation on grain number and weight (averaged for cultivar and *Fusarium* inoculum treatment). Glasshouse experiment–1988.

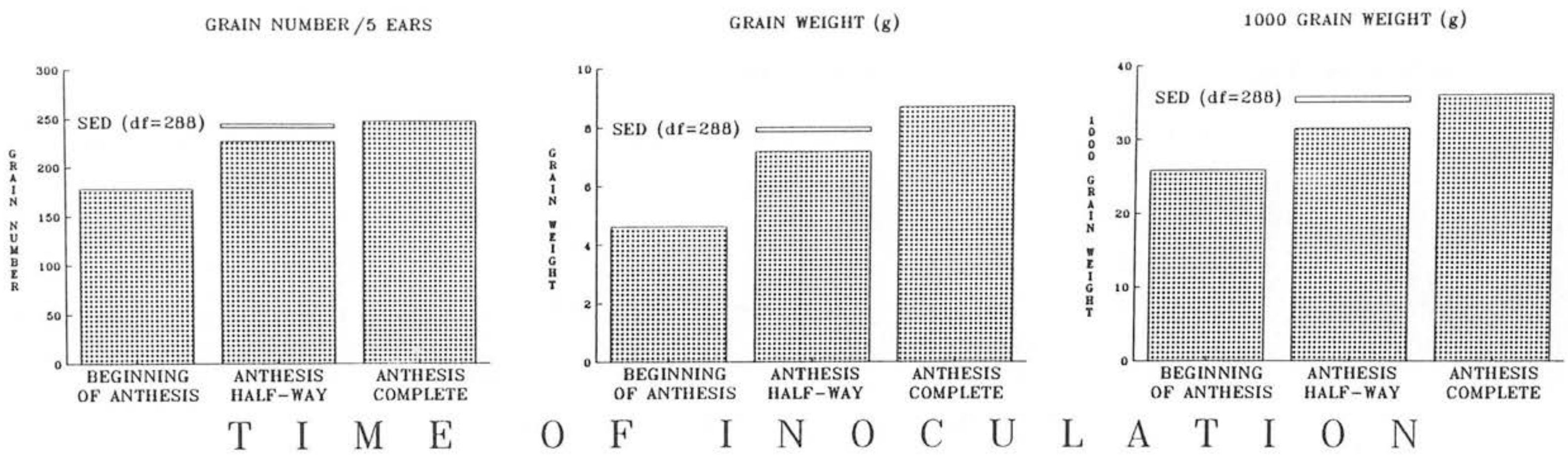


FIGURE 4.8. Grain number and weight in relation to cultivar and fungal inoculum treatment (averaged for time of inoculation). Glasshouse experiment–1988.

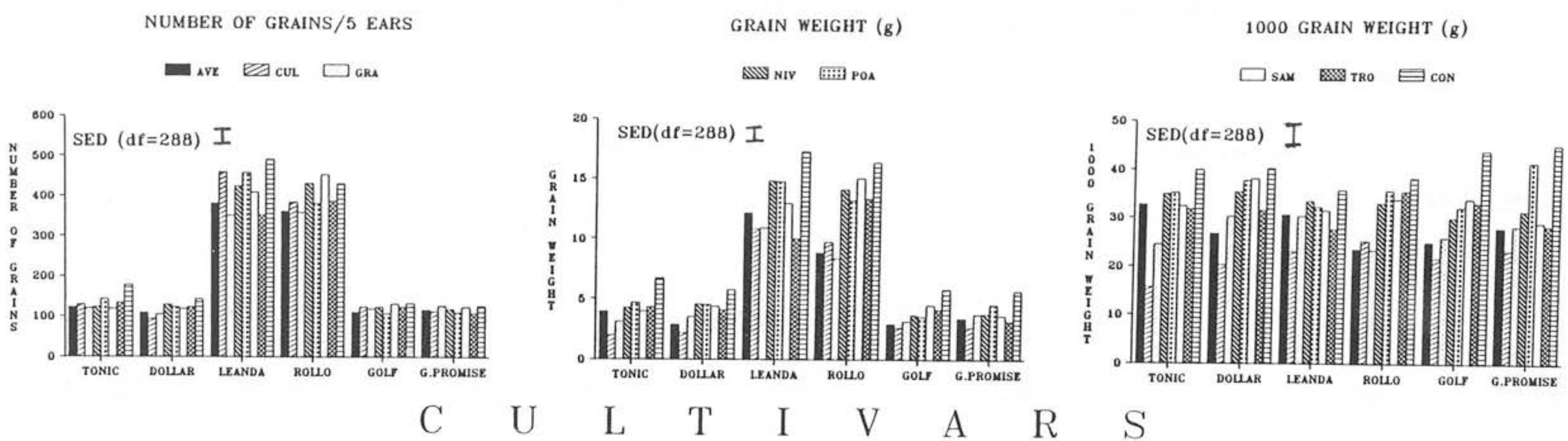


FIGURE 4.9 Grain and weight in relation to cultivar and time of inoculation (averaged for species of fungi). Glasshouse experiment–1988.

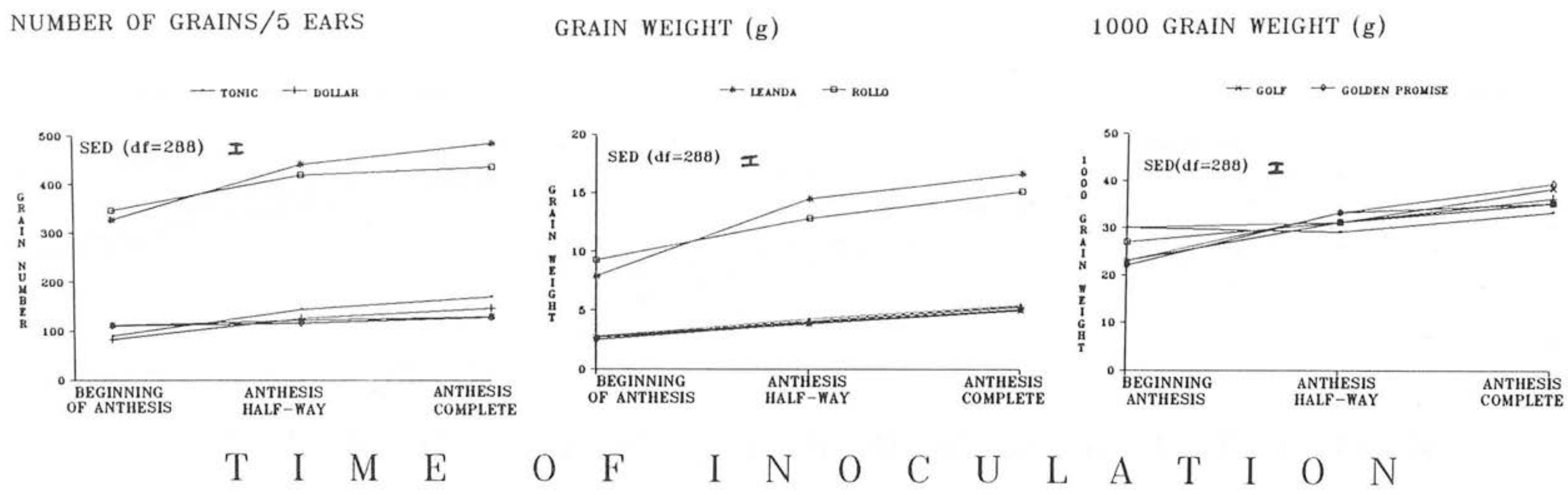
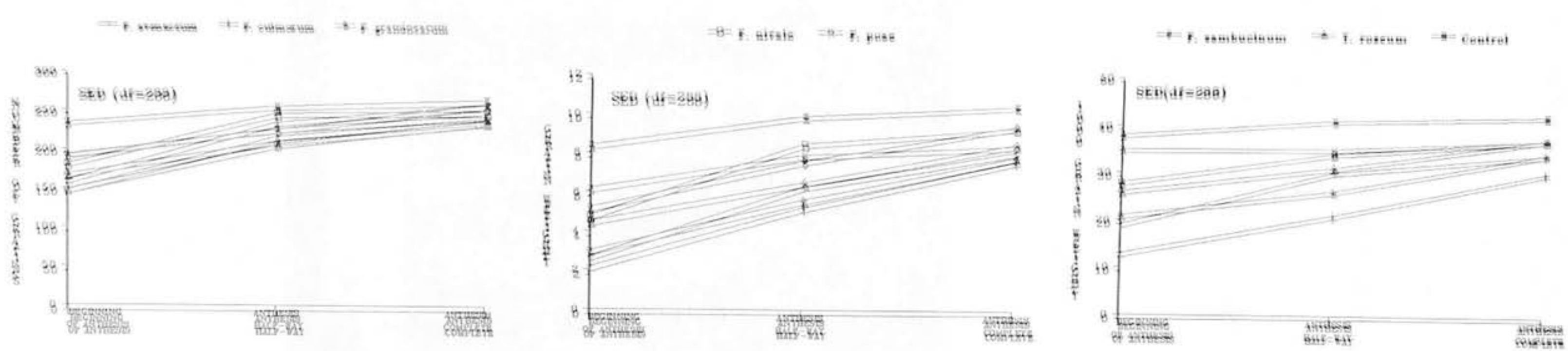


FIGURE 4.10 Grain number and weight in relation to species of fungi and time of inoculation (averaged for cultivar host). Glasshouse experiment–1988.

NUMBER OF GRAINS/5 EARS GRAIN WEIGHT (g) 1000 GRAIN WEIGHT (g)



T I M E O F I N O C U L A T I O N

with different fungal species, however, produced significant differences in grain weight and size but not in the grain number (Appendices VIIIa-VIIIc): a significant interaction was observed between *T. roseum* treatment and fungal species with regard to 1000 grain weight.

Again, *F. culmorum* caused the greater decrease in the weight of grain followed by *F. avenaceum* and *F. graminearum* (Figure 4.11, Plate 4.5). Compared with the control, *T. roseum* seemed to adversely affect yield, while *F. nivale, F. poae* and *F. sambucinum* caused only a very slight reduction (Figure 4.11). When *T. roseum* was inoculated 1 week before inoculation of *Fusarium* species the adverse effect of *F. culmorum* on 1000 grain weight was lessened (Figure 4.12).

PLATE 4.5. Effect of ear inoculation with different fungal species at mid-anthesis on number and size of barley grain, cv. Camargue.

FIGURE 4.11. Effect of ear inoculation with different fungal species on grain number and weight (averaged for host cultivar, time of inoculation and *T. roseum* treatment). Glasshouse experiment–1989.

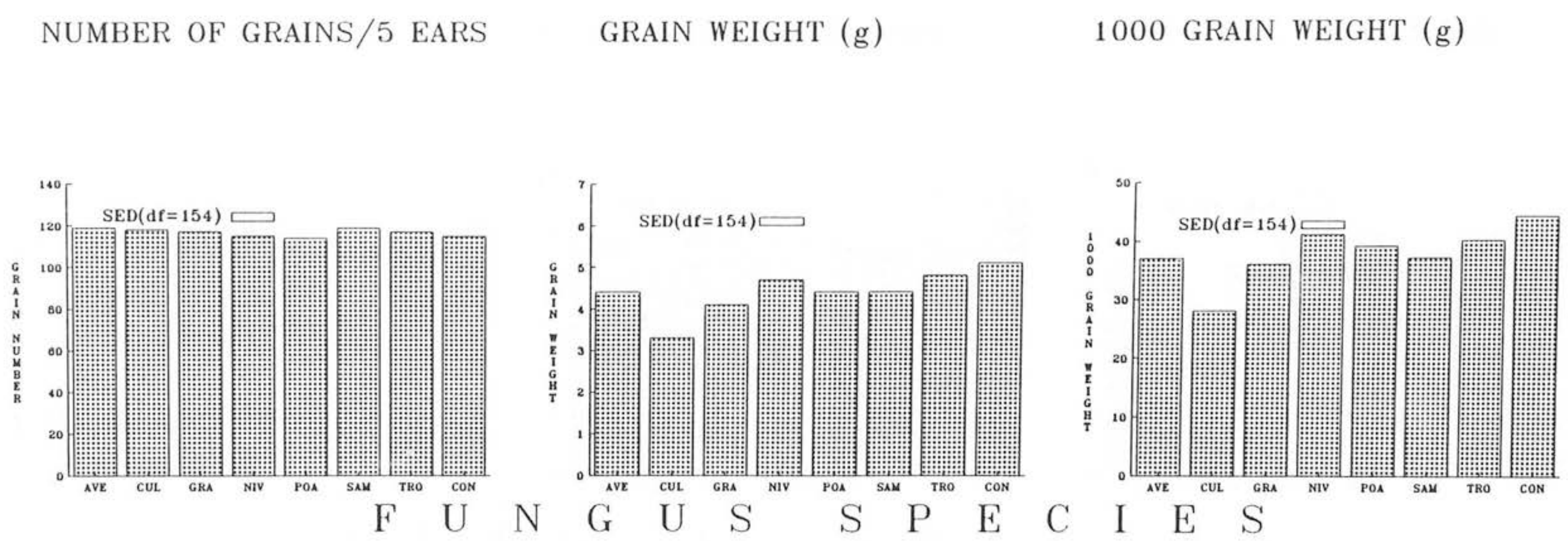
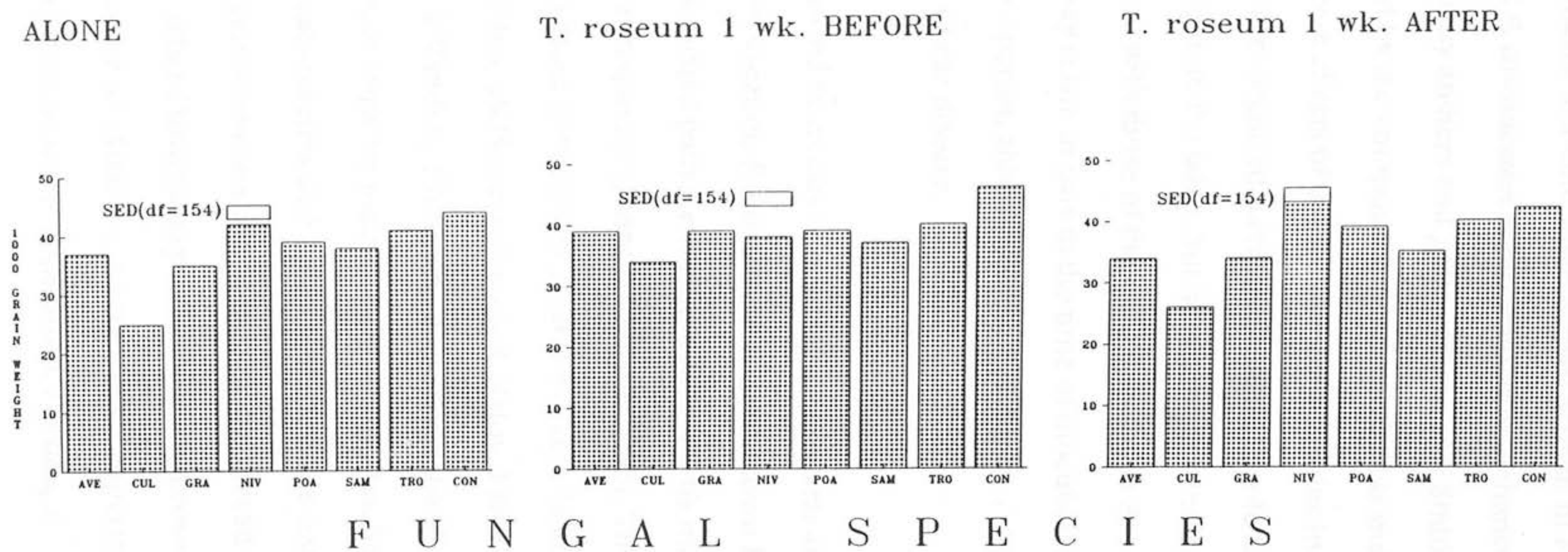


FIGURE 4.12. Effect of ear inoculation with different fungal species and *T. roseum* treatment on the 1000 grain weight (averaged for host cultivar and time of inoculation).



4.4. DISCUSSION

In these experimental studies inoculation of ears with *Fusarium* species were carried out over the period of anthesis, at a time when hyphal growth of *F, culmorum*, *F. graminearum* and *F. avenaceum* is reported to be enhanced by stimulatory compounds produced by anthers and pollen (Strange & Smith, 1978a; 1978b). *F. nivale* is not stimulated by the compounds concerned. This may account for the more severe adverse effects of the former three species in the present work, in keeping with their recognized pathogenic status (Table 2.17). *F. nivale* is also classified as a pathogen in the table, but its relatively minor effects on grain development accord more with those of the weak pathogens *F. sambucinum* and *F. poae*: this may relate in part to the time of inoculation being less conducive to infection by this species, although Strange & Smith (1978a) do not regard this fungus as a cause of ear disease.

Fusarium species are well recognized as causes of head blight of wheat and barley, and *F. culmorum, F. graminearum, F. nivale* and *F. avenaceum* have been generally identified as the principal pathogens although *F. nivale* may possibly be responsible at a lower frequency (Jones & Clifford, 1983). The results of the present work are similar to those obtained by several workers (Atanasoff, 1920; Wiese, 1977; Stack & McMullen, 1985; Strausbaugh & Maloy, 1986; Wilcoxson, Kommedahl, Ozmon & Windels, 1988) who also found that *F. culmorum* and/or *F. graminearum* were the most pathogenic species. Stack & McMullen (1985), inoculated wheat spikelets with many of the species tested in this study and found that only *F. graminearum* and *F. culmorum* spread from the inoculated spikelet. Each of their other *Fusarium* species caused necrosis only in the inoculated spikelets. Wilcoxson *et al.* (1988), in a very similar experiment, found that in addition to *F. graminearum* and *F. culmorum, F. poae, F.*

sambucinum, F. semitectum and *F. sporotrichioides* caused a few spikelets to become necrotic other than those that were inoculated.

The inoculation and incubation method used in these series of experiments facilitated infection and spread of the fungi from one spikelet to another, as they provided a high spore load with a high humidity and a temperature which is found in warmer summers. Bennett (1928) found that when inoculating ears with a suspension of conidia from sporodochia applied by means of an atomiser, both *F. culmorum* and *F. avenaceum* became established, and there was no apparent difference in what he termed virulence of the two species, or in the nature and appearance of the lesions produced. He also found that most of the florets infected at flowering time bore no grains, whilst many of those infected after produced shrivelled grains. In the results of the 1987-89 experiments grain number was generally not affected by *F. culmorum*, unless with early inoculation, but grain weight was markedly reduced by this fungus in all three years. *F. avenaceum* and *F. graminearum* tended, however, to reduce grain number but the effect on grain size was less than that for *F. culmorum*. The reasons for this variation in effect between the three species is difficult to explain .: Strange & Smith (1978a) have indicated that different compounds from the flower may be involved in the stimulation of these species and if such compounds are released at different times they may cause a variation in the time of fungal activity; it is also possible that *F. avenaceum* and *F. graminearum* are more damaging to the ovules and grain initials while *F. culmorum* has more severe effects on older tissues. The reduced effect of *F. avenaceum* and *F. graminearum* on grain size may be partly attributable to compensatory growth in surviving grain when grain numbers and, thus, competition for assimilates are less.

In considering further the effect of inoculation with *F. nivale*, it has been stated by several workers that, depending on humidity and temperature, head blight produced by this fungus can be almost invisible and be noticed solely by a loss in weight per thousand seeds. This is also accompanied by disease of the caryopsis which makes this fungus one of the most important seed-borne parasites of cereal crops for the fungus usually causes a pre-emergence damping-off (Noble & Montgomerie, 1956; Hewett, 1983; Rennie, Richardson & Noble, 1983). In some countries, e.g. Germany, this fungus has been said to have become the main cause of severe symptoms of head blight but, as found by Duben & Fehrmann (1979), in these series of experiments *F. nivale* failed to produce head blight in most of the tested cereals. One possible explanation might be that this fungus was inhibited by the usually high temperatures in the glasshouses at the time of inoculation. Cassini (1981), reported that because *F. nivale* is a poor competitor, natural or artificial inoculations of this fungus may very well be aborted by saprophytes or other species of *Fusarium* when the temperatures are greater than 15-18^{o}C. The temperatures in the glasshouses ranged from 17 to 25^{o}C which according to this worker might by too high a temperature. Bateman (1979, 1983) showed that common saprophytes, especially *Alternaria*, reduced the colonization of the seed in the ear. Natural infection of grain in the ear is probably never high. Millar & Colhoun (1969b), under experimental conditions found only a 30% of the seeds became infected by *F. nivale* even though every tiller of a wheat variety Viking bore numerous perithecia and conidia were conspicuous on the ears. They also found that a maximum of 31% of infected seeds was obtained when developing ears of that variety at growth stages 'flowering to milky ripe' were artificially inoculated with conidia of *F. nivale*. Bennett (1933), found, under conditions of artificial inoculation, that younger ears are less liable to infection than older ones, especially in barley, apparently because of the failure of inoculum to adhere to the more waxy surface.

With respect to time of inoculation, earlier treatment tended to cause more severe reductions in grain development, especially in the case of the pathogenic species *F. culmorum* and *F. avenaceum* but also with *F. nivale*. It should be noted that in control plants, earlier spraying with water alone and covering with bags showed a tendency to give poorer grain development suggesting that the inoculation procedure itself had some adverse effect on subsequent ear performance: this, however, did not appear to be a large effect.

The results for *T. roseum* suggested that it behaves as a weak pathogen of cereal inflorescences, ranking more or less with *F. poae* and *F. sambucinum*. When it was applied before or after inoculation with *Fusarium* species this fungus had no obvious overall effect except in the case of 1000 grain weight which was reduced to a smaller extent by *F. culmorum* when *T. roseum* was applied 1 week before inoculation. This trend was also seen, although the effects were non-significant, with *F. graminearum* and *F. avenaceum*. It is possible that *T. roseum* shows some antagonism to these species or that it interferes with host stimulation of these *Fusarium* pathogens.

Interactions between fungal inoculation treatment and host species and cultivar were observed only in 1988 when cultivars of oats tended to show a relatively greater reduction in grain weight yield than other cereals in response to inoculation with pathogenic *Fusarium* species. Also, the oat cultivar Leanda appeared more severely affected by *T. roseum* than other hosts. In general, however, there appears to be little evidence of important variation in host susceptibility to *Fusarium* species among the cultivars tested.

F. poae is regarded as a weak parasite or saprophyte and the only disease symptom with which it is associated in cereals is a lesion on wheat glumes. This fungus tended to be unable to produce any effect on number or weight of ears of the several tested cereal varieties. Along with *F. poae, F. sambucinum* is also classified as a weak pathogen but from the evidence of these studies it would appear to be rather more damaging to ears than the former fungus.

SECTION 5

THE EFFECT OF EAR INOCULATION OF CEREALS WITH DIFFERENT FUNGAL SPECIES ON SEED AND SEEDLING PERFORMANCE

5.1 INTRODUCTION

The experimental work in this section is concerned with the assessment of seed germination and subsequent seedling growth, using samples of seed from cereal plants subjected to the various ear inoculation treatments described in the previous section, Seed health tests were also carried out to determine the rate of recovery from fungal inoculum applied to ears on the harvested seed.

Fusarium species are well known as causes of quantitative and qualitative damage in seed production, seed vigour being one of the recognized components of seed quality which is affected by these fungi. The concept of seed vigour may be invoked to described variation in the emergence and growth performance of seed lots which have similar germination capacities (Heydecker, 1972): vigour tests are designed to differentiate between seed lots of high and low performance potential in field soil. Germination test results are supposed to predict performance under favourable conditions but field conditions are generally sub-optimal due to the existence of potential pathogens and adverse edaphic factors (Heydecker, 1969). Various approaches have been used to gain, compared with routine germination tests, an improved prediction of seed performance in the field including soil tests (Brown, 1928), germination rate (Stahl, 1936), conductivity tests (Perry, 1967; 1969) and plumule growth measurements (Perry, 1977).

The impact of pathogens such as fungi on seed vigour is enormous: besides having a direct effect, they can also indirectly influence vigour through effects on related factors such as seed size. From an ecological point of view Christensen & Kaufmann (1969) divided the fungi which invaded seed into two general groups, field fungi and storage fungi. Field fungi are those that invade seeds as they are developing in the field or after seed has matured but before harvest. The common genera of field fungi include *Fusarium*: they may reduce seed size and germination capacity, and cause discolouration, seed rots, seed abortion and physiological alterations (Neergaard, 1977). Fungal attacks on grain primordia, especially between flowering and grain maturation, lead to damage, and although seed may be formed it is of reduced size viability: Neergaard (1977) described this effect in ryegrass for *F. culmorum*. Neergaard also associated *F. avenaceum* and *F. moniliforme* with seed rots and the prevention of germination and *F. moniliforme* with necrotic lesions which radiate from the embryo in maize. De Tempe (1958) found that high infection levels of wheat and barley by *Fusarium* species, as determined by blotter tests, caused a significant reduction in emergence under field conditions which was reflected in yield decreases. Fritz (1966) recorded considerable reductions in germination of spring wheat due to *F. nivale*, in laboratory tests at low temperature. Other field fungi implicated in adverse effects on cereal seed include *Drechslera*, *Septoria* and *Ustilago* species (Neergaard, 1977).

The aims of the experimental studies were to compare the effects of ear inoculation with different *Fusarium* species on the performance of seed of barley, oats and wheat cultivars, taking into account different times of inoculation and possible interactions with *T. roseum*

The experiments are considered under the following headings:

(a) The effects of ear inoculation with different *Fusarium* species at different growth stages on seed and seedling performance in cultivars of barley, oats and wheat;

(b) The effect of *Fusarium* and *Trichothecium roseum* ear inoculation at different growth stages on seed and seedling performance in cultivars of barley, oats and wheat;

(c) The effects of *Fusarium* and *Trichothecium roseum* ear inoculation at different growth stages on seed and seedling performance of barley cvs. Camargue and Sherpa.

5.2 MATERIALS AND METHODS

Experimental details to the stage of seed harvest for the three experiments are described in Section 4.

5.2.1 Experiment 1.

Seeds from each replicate of each experimental treatment harvested from glasshouse experiment in 1987 were used for seed health tests and seedling health tests.

In each seed health test 20 seeds from each treatment were plated on PDA, 10 seeds without surface sterilization and 10 seeds with surface sterilization from the four replicates. Surface sterilization was done by immersing the seeds in sodium hypoclorite/ethyl alcohol with approximately 1.5% available chlorine and 20% ethyl alcohol for 5 minutes. Following sterilization the seeds were placed on to a piece of paper towel to drain the excess of solution and then plated on agar. The agar plates containing seeds were incubated for 7 days at a room temperature of $20^{o}C$ ($\pm 5^{o}C$). Assessments of each seed health test was made by scoring the percentage of seeds with typical colonies relating to the respective inoculation treatment and the percentage with colonies of contaminants from ear controls.

In the seedling health test, each combination of cultivar, fungus and time of inoculation treatment was represented by 25 seeds placed between two layers of 70 cm long paper towels replicated four times. The bottom layer consisted of two sheets and the top of one. The towels were saturated with tap water, the basal 2 cm folded up, and the sheets were then rolled loosely. The rolls were stood upright in a wire tray, to let excess water to drain, and kept at room temperature (20 to 25^{o}C). Each treatment was assessed after seven days based on ISTA rules (Anon, 1985). Seedlings possessing the structures considered essential to enable them to develop into mature plants under favourable field conditions were classed as normal. The number of normal seedlings was expressed as a percentage of the total number of seeds sown giving the germination percentage of the sample. All seed which failed to germinate were counted as dead and the percentage of ungerminated seeds was calculated. Seedlings with brown roots and/or brown shoots and/or seedlings without roots or shoots were classed as abnormal. Root and shoot lengths were also recorded and the average length per replicate of total number of seeds was used for the analysis of variance of the data.

5.2.2 Experiment 2

In this study on seed from the 1988 glasshouse experiment, seed health tests were carried out as in Experiment 1..

Germination evaluation was based on ISTA rules (Anon, 1985), also as in Experiment 1. Plumule length was scored as described by Perry (1977). Seed was stuck with clear rubber solution to a paper towel (70 by 22 cm) on which a centre line with 25 marked points, 2 cm apart, was drawn on the long axis. Lines were drawn at 2 cm intervals parallel with, and to one side of the centre line. One seed was stuck to each mark, orientated with the embryo away from the paper and with the apex pointing at right angles towards the parallel lines. A replicate consisted of 25 seeds. The towels were left overnight to allow the rubber solution to dry. The towels were saturated with distilled water and then rolled loosely after the basal 2 cm was folded up. The rolls were stood upright in wire trays which allowed excess water to drain. Seedling measurement was done after 7 days. The spaces between the parallel lines were assigned mean values of 1, 3, 5, 7, 9 and 11 cm according to the distance from the centre line. The number of plumule tips which lay between each pair of parallel lines were counted and mean plumule growth (cm) from the seeds were calculated as follows:

$$\frac{(n \times 1 \ldots\ldots\ldots n \times 11)}{25}$$

where n was the number of seedlings in each mean value and x 1 to x 11 were the respective mean values at 2 cm intervals.

5.2.3 Experiment 3.

Seeds of the barley cultivar Camargue from each replicate of each experimental treatment harvested from the 1989 glasshouse experiments were used for seed and seedling health tests. Separate tests were then carried out for cv. Sherpa.

Seed health tests in this experiment were carried out chiefly as in Experiments 1 and 2 but 30 seeds were plated on PDA, 15 seeds without surface sterilization and 15 seeds with surface sterilization from the three replicates.

The setting up of seedling health tests were as in Experiment 1. Each combination of fungus, inoculum type and growth stage was represented by 25 seeds plated between two layers of 70 by 22 cm paper towels replicated four times. Root and shoot lengths were recorded for each of the 25 seedlings per replicate and the averaged length was used for analysis of variance of the data. A disease severity index on roots and shoots of seedlings was calculated based on a 0-4 scale as follows:

0	Normal seedlings
1	Slight browning and slight reduction of growth
2	Extensive browning and visible reduction in seedling vigour
3	Stunted seedlings showing severe extensive browning
4	Seed decayed with no seedling growth

$$\textbf{The disease severity index (DSI)} = \frac{\text{no x 0 + no X 1+ no x 2+ no x 3 + no x 4}}{\textbf{Total seed number}}$$

where **no** was the number of seedlings in each of the respective disease grades. Seedlings showing different grades of severity are presented in Plate 5.1.

PLATE 5.1. Seedlings of barley cv. Camargue showing different degrees of disease severity.

5.3 RESULTS

From the analyses of variance of the data for seed health and seedling performance tests in the three experiments, significant main effects were observed for each of the treatment factors (Appendices IX to XII). However, there were invariably significant interactions between the factors and, in interpreting the results, main trends are indicated but only some of the interactions are considered.

5.3.1 Experiment 1. The effects of ear inoculation at different growth stages with different *Fusarium* species on seed and seedling performance in cultivars of barley, oats and wheat.

Seed health tests

The percentage recovery rates from seed for the different *Fusarium* species inoculated onto ears varied significantly between species: the highest seed infection level (an average of 71%) was found with *F. culmorum* and *F. avenaceum*. *F. graminearum, F. nivale* and *F. poae* followed in decreasing order (Table 5.1). Some *Fusarium*, usually *F. culmorum*, was isolated from control seed indicating a small amount of cross contamination. Seed sterilization reduced the recovery rate but this was not significant in the case of *F. culmorum* (Table 5.1). For other species, however, the levels of infection were reduced relative to the controls to 83% for *F. avenaceum*, 75% for *F. graminearum* and 50% for *F. nivale* and *F. poae*. Differences in levels of infection were relatively slight between the different host cultivars, averaged for the different fungal inoculation treatments, particularly for the last date of inoculation (Table 5.2). It may be seen from Table 5.2 that earlier inoculation gave higher rates of seed infection.

Table 5.1. Recovery rate (%) of inoculated *Fusarium* in relation to species and seed sterilization. Glasshouse experiment-1987.

SEED TREATMENT	FUSARIUM SPECIES AVE	CUL	GRA	NIV	POA	CON
Sterilized	59	70	46	28	22	2
Unsterilized	70	72	62	54	42	6

SED (df=577) $\pm$ 2.4

Table 5.2. Recovery rate (%) of inoculated *Fusarium* in relation to cultivar and time of inoculation. Glasshouse experiment-1987.

CULTIVARS	TIME OF INOCULATION FIRST	SECOND	THIRD
Golden Promise	56	46	35
Club	62	47	34
Dollar	60	40	32
Trafalgar	53	44	31
Leanda	52	39	35

SED (df=577) $\pm$ 2.7

Seed germination and seedling growth

The percentage of seed failing to germinate varied with cultivar, fungal inoculum treatment and time of ear inoculation, but there were significant interactions between these factors. Cultivars showed more or less similar, low rates of germination failure from uninoculated ears or those inoculated with *F. nivale* or *F. poae*, but where ears had been inoculated with *F. avenaceum*, *F. culmorum* or *F. graminearum* the two wheat cultivars showed higher rates of germination failure than other hosts (Table 5.3). Table 5.3 also shows that the highest rate of germination failure was associated with *F. culmorum* followed by *F.*

graminearum and *F. avenaceum*. The effects of these three species were most severe with early inoculation (Table 5.4). The pattern of response for seedling abnormality incidence tended to follow the same pattern as that for germination failure (Tables 5.3 and 5.4) in that adverse effects were associated primarily with *F. culmorum* followed by *F. avenaceum* and *F. graminearum* but obvious differences in host response were less evident. Furthermore *F. nivale* gave a relatively high incidence of abnormal seedlings in the oat cultivar, Leanda. More seedling abnormality occurred from early times of inoculation with the various fungal species.

The effects of the fungi on seedling root and shoot length of different cultivars are shown in Tables 5.3 and 5.4: adverse effects are again most marked with *F. culmorum* but evident with *F. avenaceum* and *F. graminearum*. It may also be seen that *F. nivale* and to a lesser extent *F. poae* also caused reduced root and shoot growth relative to the controls. As with other criteria the effects of ear inoculation with fungi were greater with earlier inoculation.

5.3.2 Experiment 2. The effects of *Fusarium* and *Trichothecium roseum* ear inoculation at different growth stages on seed and seedling performance.

Seed health tests

Seed from the 1988 glasshouse experiment showed high rates of recovery of *F. culmorum*, while *F. avenaceum, F. graminearum* and *F. sambucinum* showed moderately high rates (Table 5.5). The percentage figures for *F. nivale, F. poae* and *T. roseum* were relatively low, while control seed showed a higher degree of cross contamination than in the previous year. Surface sterilization of seed reduced the recovery rate except for *F. sambucinum* and *T. roseum* (Table 5.5).

Table 5.3. Seed performance in relation to *Fusarium* species and cultivar. Glasshouse experiment-1987.

CULTIVARS	FUSARIUM SPECIES AVE	CUL	GRA	NIV	POA	CON
% UNGERMINATED SEED: SED (DF=267) ± 1.7						
Dollar	17	42	24	3	4	3
Club	15	23	17	3	5	2
Golden Promise	6	15	7	2	2	1
Trafalgar	6	7	7	1	1	2
Leanda	7	10	7	5	3	5
% ABNORMAL SEEDLINGS: SED (DF=267) ± 2.1						
Dollar	33	38	21	4	3	2
Club	27	38	36	6	5	<1
Golden Promise	19	21	16	2	1	1
Trafalgar	23	33	16	8	3	1
Leanda	18	24	22	17	5	2
SHOOT LENGTH (cm) : SED (DF=267) ± 0.3						
Dollar	6.5	3.2	5.7	8.6	8.8	3.9
Club	4.7	3.1	4.2	6.9	7.3	8.1
Golden Promise	5.2	4.3	5.0	8.6	8.9	10.7
Trafalgar	5.3	4.1	5.7	6.3	7.4	8.9
Leanda	3.7	2.6	4.1	5.5	8.2	9.0
ROOT LENGTH (cm): SED (DF=267) ± 0.3						
Dollar	3.5	2.3	3.3	6.4	6.7	6.8
Club	3.1	2.2	2.9	6.2	6.6	7.5
Golden Promise	4.0	2.8	3.9	6.2	7.2	7.7
Trafalgar	3.7	3.2	3.9	4.8	5.9	7.1
Leanda	3.7	2.7	4.3	4.5	6.3	6.6

Table 5.4. Seed performance in relation to *Fusarium* species and time of inoculation. Glasshouse experiment-1987

	FUSARIUM SPECIES					
CULTIVARS	AVE	CUL	GRA	NIV	POA	CON
% UNGERMINATED SEED: SED (DF=267) $\pm$ 1.7						
First	19	31	24	4	4	3
Second	7	16	8	3	2	2
Third	5	12	5	2	3	2
% ABNORMAL SEEDLINGS: SED (DF=267) $\pm$ 1.6						
First	33	37	34	16	7	2
Second	24	30	18	4	3	1
Third	15	25	15	2	1	0
SHOOT LENGTH (cm) : SED (DF=267) $\pm$ 0.3						
First	4.2	2.4	3.8	6.9	7.6	8.5
Second	5.0	3.3	4.8	7.1	8.3	9.4
Third	6.0	4.7	6.2	7.6	8.5	9.4
ROOT LENGT (cm): SED (DF=267) $\pm$ 0.2						
First	3.1	1.6	2.9	5.0	6.2	6.6
Socond	3.4	2.7	4.0	5.9	6.6	7.0
Third	4.3	3.6	4.1	5.9	6.9	7.8

In considering the incidence of inoculated fungi in relation to cultivar and time of inoculation there was a general trend for early inoculation to give higher percentages but this applied more particularly to wheat cultivars (Table 5.6). With barley and oat cultivars late inoculation also gave a high incidence of inoculated fungi. However, there was a significant interaction between time of inoculation and seed sterilization treatment. Later times of inoculation gave less infection on sterilized seed, 48, 37 and 33 % (SED ± 3.4) for early mid- and late inoculation respectively. However, with untreated seed the corresponding figures were 54, 47 and 65%. This large amount of contamination from late inoculation for untreated seed was observed to be particularly marked in barley and oat cultivars.

Table 5.5. Recovery rate of inoculated *Fusarium* in relation to species and seed sterilization. Glasshouse experiment-1988.

SEED TREATMENT	*FUSARIUM* SPECIES AVE	CUL	GRA	NIV	POA	SAM	TRO	CON
Sterilized	51	79	50	17	23	61	22	12
Unsterilized	80	93	67	34	40	66	23	26

SED (df=931) ± 2.7

Table 5.6. Recovery rate (%) of inoculated fungi in relation to cultivar and time of inoculation. Glasshouse experiment-1988.

CULTIVARS	TIME OF INOCULATION FIRST	SECOND	THIRD
Tonic	59	53	44
Dollar	48	45	35
Golf	50	38	48
Golden Promise	53	44	49
Rollo	48	33	54
Leanda	49	39	48

SED (df=931) ± 2.9

Seed germination and seedling growth

With regard to the seed responses to ear inoculation it was observed that germination failure was very high with *F. culmorum* averaging 60%, while *F. avenaceum*, *F. graminearum* and *T. roseum* and to a very slight extent, *F. sambucinum*, gave significantly higher average percentages of ungerminated seed relative to the controls (Table 5.7). *F. nivale* and *F. poae* had no significant effect on germination rate. Cultivars responded in a similar way with the exception of the wheat cultivar, Tonic, which showed better germination with *F. culmorum* than other cultivars and the oat cultivar, Rollo, which was not affected to the same extent as other cultivars by *F. avenaceum*. For all fungi having an adverse influence on germination, the effects were greater with earlier inoculation (Table 5.8).

The incidence of abnormal seedlings was increased relative to the controls with all fungi, particularly *F. graminearum* (Table 5.7): lower percentages were associated with *F. poae* and *T. roseum* than with other fungi. Earlier inoculation gave a greater frequency of abnormal seedlings except in the case of *F. culmorum* which gave, however, a high rate of germination failure (Table 5.8). Cultivars from control plots showed some variation in frequency of occurrence of abnormal seedlings, Golden Promise showing the highest incidence (Table 5.7).

F. culmorum gave a substantial reduction in plumule growth, while *F. graminearum* and *F. avenaceum* gave moderate reductions: these effects were greater in the barley cultivars (Table 5.7). All other fungal inoculation treatments appeared to give some depression in plumule growth on average but this was not

Table 5.7. Seed performance in relation to fungal species and cultivars. Glasshouse experiment-1988.

CULTIVARS	AVE	CUL	GRA	NIV	POA	SAM	TRO	CON
			FUNGAL SPECIES					
% UNGERMINATED SEED: SED (df=429) ± 2.8								
Tonic	24	39	17	6	5	13	20	11
Dollar	26	60	15	10	11	7	23	4
Golf	24	62	12	8	8	10	15	4
Golden Promise	24	66	21	10	9	8	21	9
Rollo	12	59	15	3	3	11	15	7
Leanda	24	76	16	9	8	13	19	11
% ABNORMAL SEEDLINGS: SED (df=429) ± 2.1								
Tonic	26	42	36	15	10	23	5	6
Dollar	19	14	44	22	7	23	8	4
Golf	25	21	49	18	16	28	19	3
Golden Promise	32	34	46	21	21	33	24	12
Rollo	54	18	58	19	19	31	23	8
Leanda	34	19	50	24	24	29	11	4
PLUMULE LENGTH (cm): SED (df=429) ± 0.5								
Tonic	7.0	3.5	6.8	7.8	7.8	6.5	7.5	8.0
Dollar	6.2	1.5	6.0	7.9	8.1	6.8	7.5	8.2
Golf	4.6	1.1	3.6	8.1	8.0	6.8	8.1	8.2
Golden Promise	2.9	1.1	3.6	5.6	7.5	7.0	7.3	8.7
Rollo	5.5	2.6	5.1	8.1	8.2	7.2	8.1	8.1
Leanda	7.2	2.2	4.6	7.3	7.7	7.7	8.2	8.1

apparent in all cultivars (Table 5.7). Generally earlier fungal inoculation had a greater adverse effect on plumule length (Table 5.8).

5.3.3 Experiment 3. The effects of *Fusarium* and *Trichothecium roseum* ear inoculation at different growth stages on seed and seedling performance in two cultivars of barley.

The analyses of results from Experiments 3 relating to the effects of different species of *Fusarium* and *Trichothecium roseum* on seed health and growth of shoots and roots of the barley cvs. Camargue and Sherpa are summarized in Appendices XI and XII.

Seed health tests (Camargue)

Seed from glasshouse experiment 1989 showed the highest percentages of infection when ears were inoculated with *F. culmorum* and *F. sambucinum*, while intermediate infection rates were found in the case of *F. avenaceum* and *F. graminearum*. *F. nivale, F. poae* and *T. roseum* showed similar slight to moderate levels of infection (Table 5.9). In comparing the effect of seed sterilization a reduction in recovery rate was observed with the use of seed sterilization in most of the fungi inoculated but this effect was not significant in the case of *F. avenaceum*, *F. culmorum* and *F. graminearum* (Table 5.9, Plate 5.2).

Table 5.8. Seed performance in relation to fungal species and time of inoculation. Glasshouse experiment-1988.

CULTIVARS	AVE	CUL	GRA	NIV	POA	SAM	TRO	CON
				FUNGAL SPECIES				
% UNGERMINATED SEED: SED (DF=429) $\pm$ 2.0								
First	37	83	21	9	9	11	33	9
Second	18	61	17	8	8	11	14	7
Third	14	38	11	6	6	9	8	8
% ABNORMAL SEEDLINGS: SED (DF=429) $\pm$ 2.2								
First	45	16	63	31	20	38	22	7
Second	31	25	42	22	17	28	15	5
Third	18	33	36	15	12	18	8	6
PLUMULE LENGTH (cm): SED (DF=429) $\pm$ 0.2								
First	5.1	0.8	3.9	7.2	7.8	6.6	7.4	8.1
Second	5.6	2.1	4.8	7.3	8.0	7.0	7.8	8.1
Third	6.0	3.0	6.2	7.9	7.9	7.4	8.2	8.4

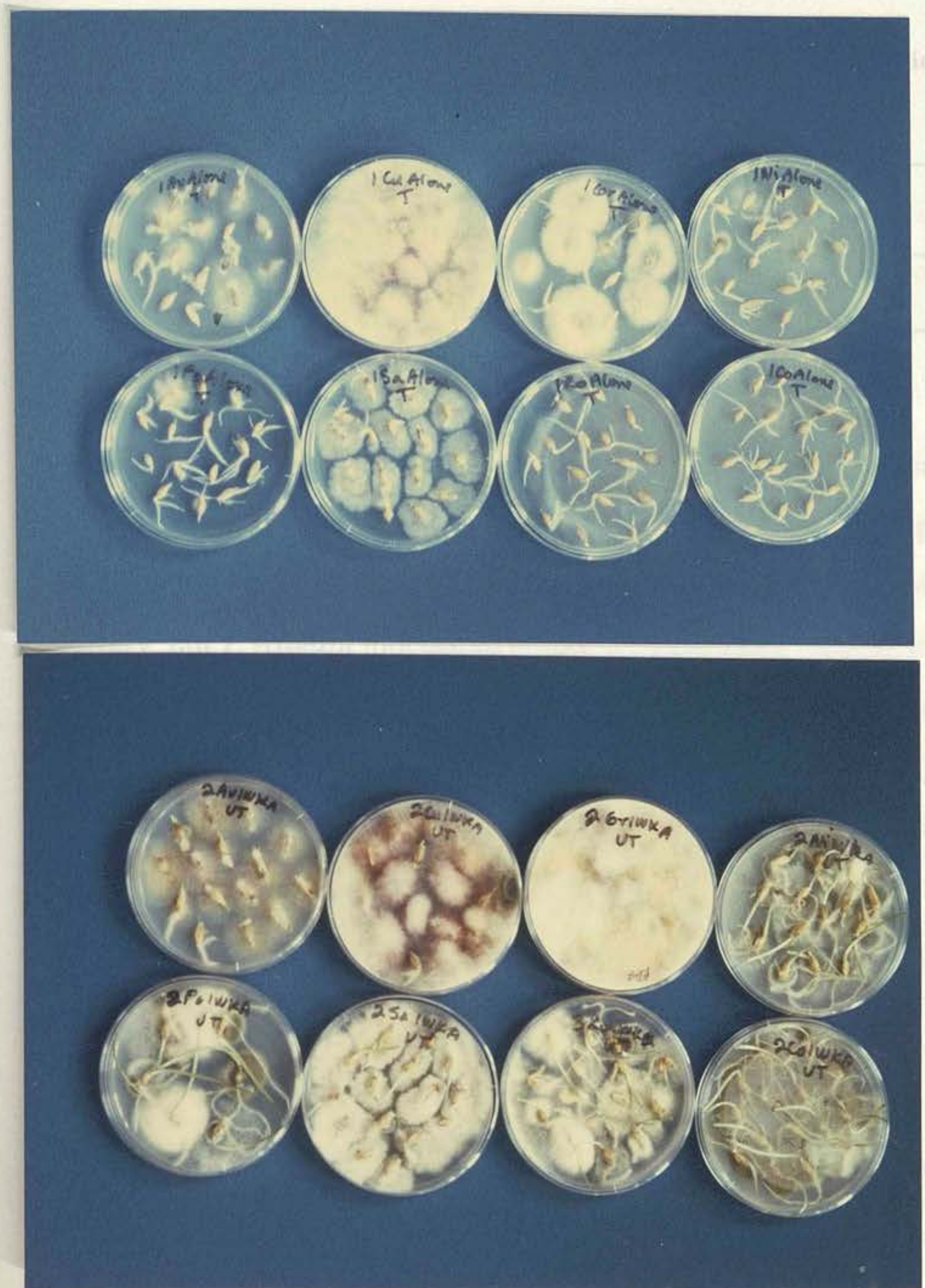


PLATE 5.2. Recovery of fungal species from barley seed, cv. Camargue, following ear inoculation to show the effect of surface sterilization:

above- Sterilized

below- Untreated

Table 5.9. Recovery rate (%) of inoculated fungi in relation to species and seed sterilization. Glasshouse experiment-1989 (Camargue).

SEED TREATMENT	FUNGAL SPECIES AVE	CUL	GRA	NIV	POA	SAM	TRO	CON
Sterilized	58	82	61	29	32	74	21	7
Unsterilized	54	88	68	38	40	86	33	6

SED (df=314) ± 3.4

With regard to the interaction between fungal species and *T. roseum* significant differences in the recovery rate were obtained. On average fungal species inoculated on their own and post-inoculation with *T. roseum* gave similar rates of recovery, but *T. roseum* inoculated before the fungal species gave lower rates. This trend, however, applied only in the case of *F. avenaceum, F. graminearum, F. poae* and *F. sambucinum*. The combination *F. culmorum* and *T. roseum* post-inoculation treatment gave significantly greater recovery rates than both fungal species alone and pre-inoculation with *T. roseum*. *F. nivale* seemed to be adversely affected by the post-treatment with *T. roseum*. No significant differences in recovery rates were observed between the controls (Table 5.10).

TABLE 5.10. Recovery rate (%) of inoculated fungi in relation to species and *Trichothecium roseum* treatment. Glasshouse experiment-1989 (Camargue).

INOCULUM TREATMENT	FUNGAL SPECIES AVE	CUL	GRA	NIV	POA	SAM	TRO	CON
ALON	61	80	66	40	33	94	34	4
PRET	40	80	59	34	44	59	22	8
POST	66	95	69	27	31	87	26	8

SED (df=213) ± 4.2

Disease severity index and seedling growth (Camargue)

When recording the disease severity index on shoots and roots it was observed that only the apparently most pathogenic species of *Fusarium* namely *F. culmorum, F. avenaceum* and *F. graminearum* produced severely diseased shoots and roots (Figure 5.1). This was most marked on seeds from ears inoculated with *F. culmorum* which on average gave indices of disease severity of 83% and 72% on shoots and roots respectively. The indices of disease severity of *F. nivale, F. poae, F. sambucinum* and *T. roseum* were relatively low, particularly for roots. The results for shoot and root length (Figure 5.1) show that *F. culmorum* had the greatest adverse effect on growth, while *F. avenaceum* and *F. graminearum* also seriously affected growth. Other fungi had little effect on shoot growth but slightly reduced root growth relative to the controls. On average pre-inoculation treatment with *T. roseum* was beneficial in reducing the disease severity index of shoots and of roots and in comparing root growth (Figure 5.2). When inoculation treatments were carried out near mid-anthesis they gave the highest disease severity indices and reduced shoot and root growth to the greatest extent (Figure 5.3).

The interactions between fungal species, treatment with *T. roseum* and time of inoculation for disease severity indices of shoot and roots are given in Figures 5.4 and 5.5. Figures 5.4a and 5.5a illustrate the results for fungal species tending to give more severe symptoms on shoots and roots. Only in the case of *F. culmorum* did pre-inoculation with *T. roseum* consistently reduce the index, while with *F. avenaceum, F. graminearum* and *F. sambucinum* the effects of *T. roseum* were variable or non-significant depending on both species and time of inoculation.

FIGURE 5.1. Disease severity index (%) and length (cm) of shoots and roots of barley cv. Camargue in relation to fungal species (averaged for inoculum treatment and time of inoculation).

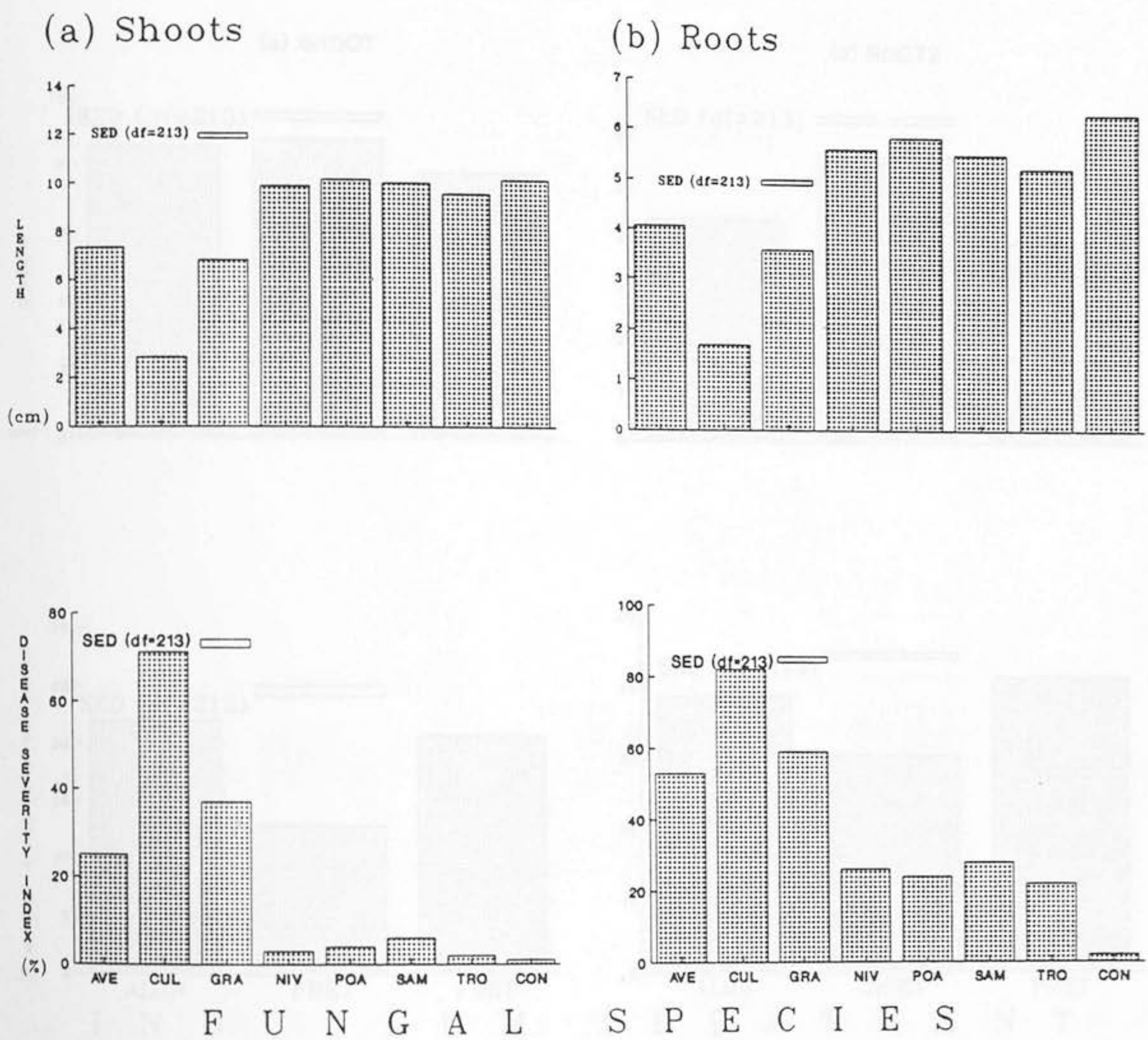


FIGURE 5.2. Disease severity index (%) and length (cm) of shoots and roots of barley cv. Camargue in relation to inoculum treatment (averaged for fungal species and time of inoculation).

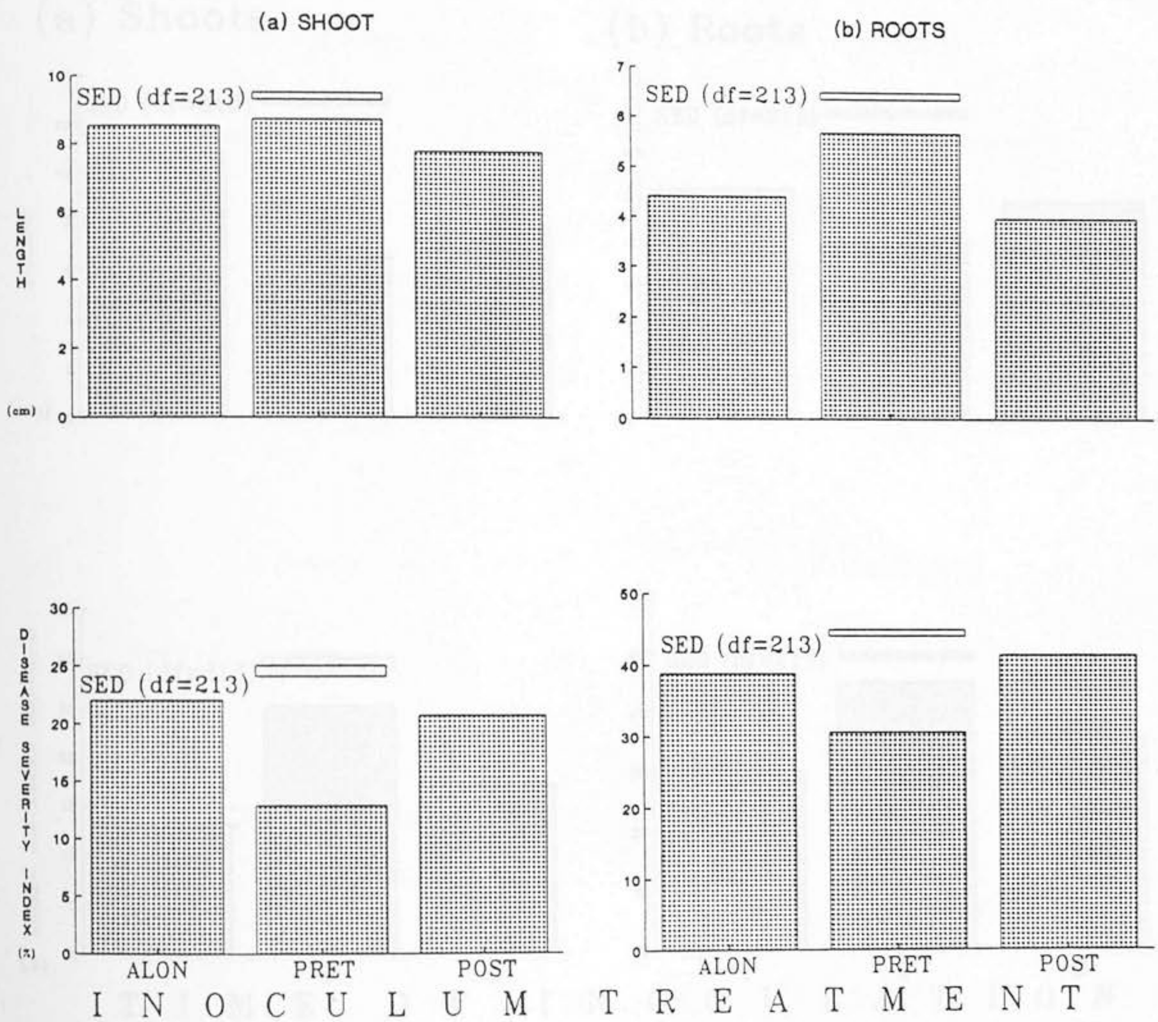


FIGURE 5.3. Disease severity index (%) and length (cm) of shoots and roots of barley cv. Camargue in relation to time of inoculation (averaged for fungal species and inoculum treatment).

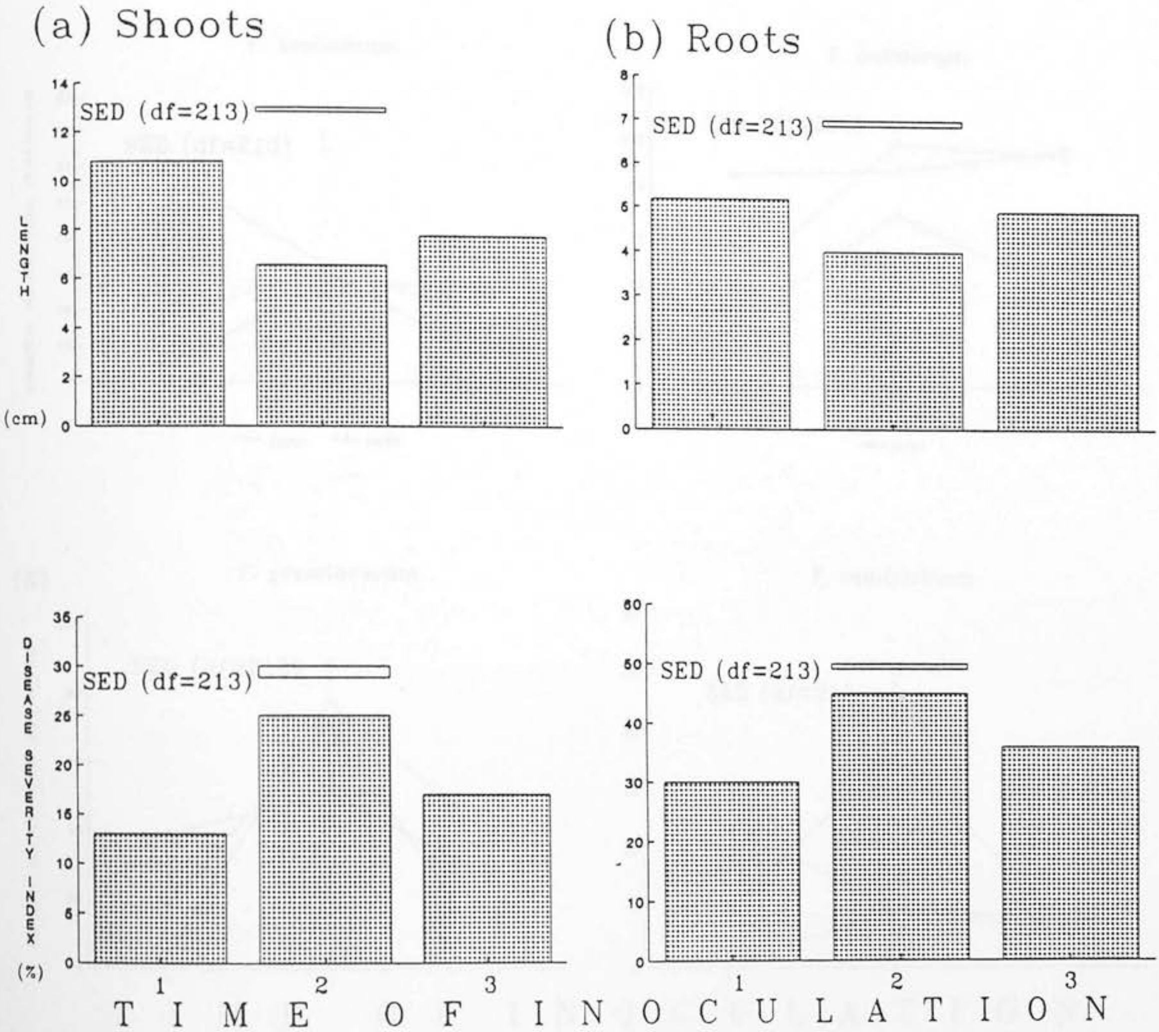


FIGURE 5.4a. Disease severity index (%) of shoots of barley cv. Camargue in relation to fungal species, inoculum treatment and time of inoculation.

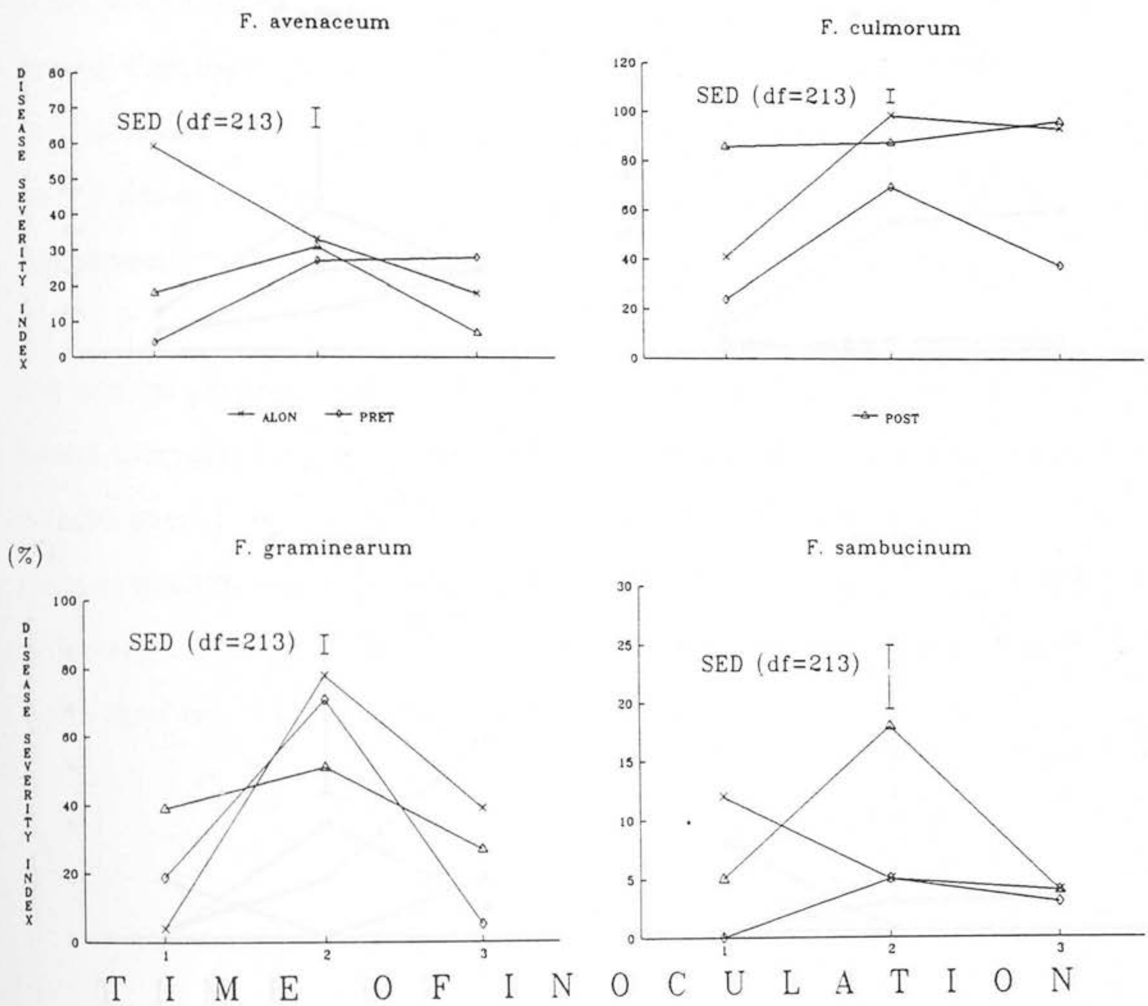
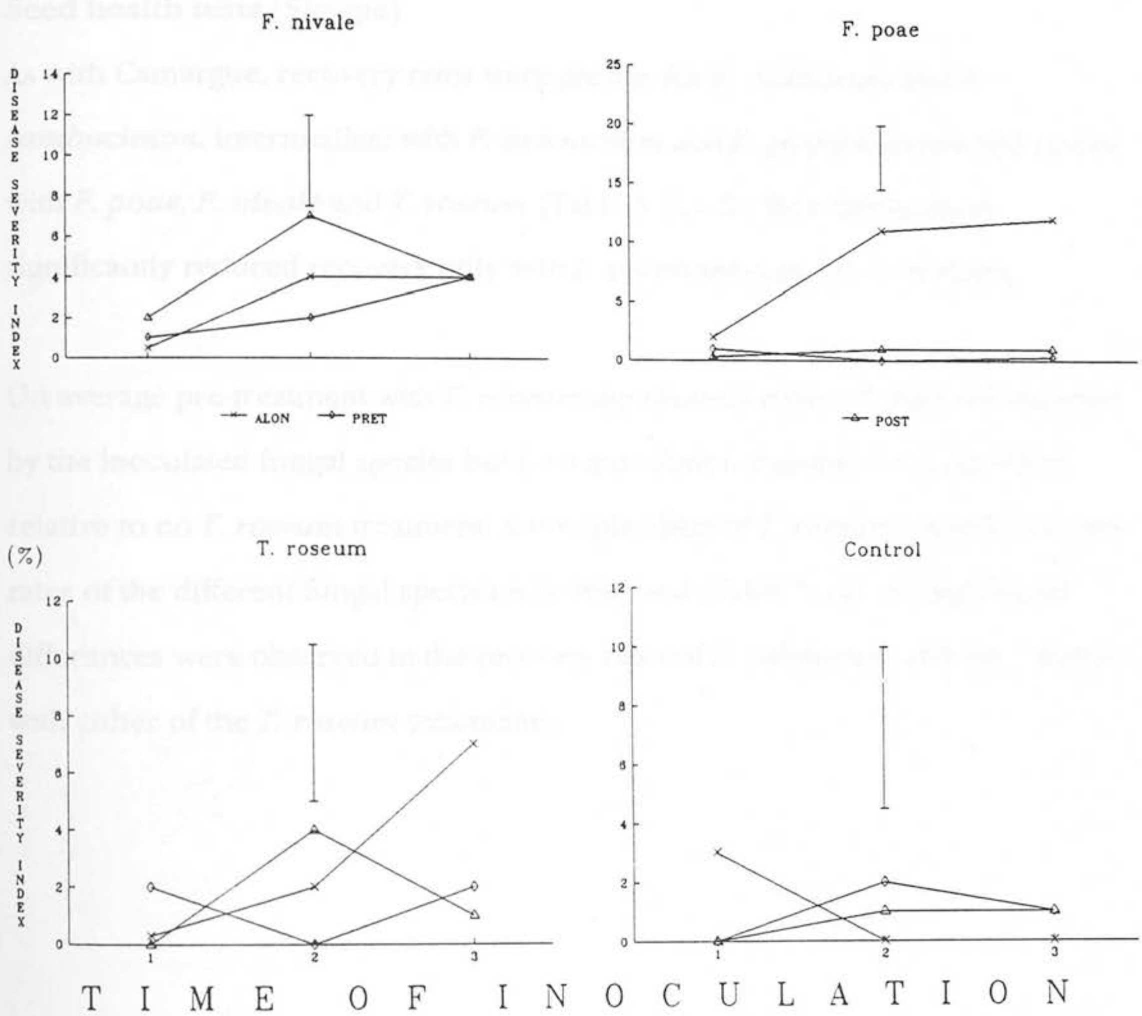


FIGURE 5.4b. Disease severity index (%) of shoots of barley cv. Camargue in relation to fungal species, inoculum treatment and time of inoculation.



With the remaining fungal species (Figures 5.4b and 5.5b) treatments with *T. roseum* again had variable effects: it tended to reduce disease severity with *F. poae* when *T. roseum* was applied either before or after inoculation; in the case of *F. nivale* there was no significant effect on shoot disease but root disease severity was reduced with pre-inoculation *T. roseum* treatment at early and late anthesis but aggravated with post-inoculation treatment at the two earlier times of inoculation. Adding *T. roseum* to its own inoculum had no effect on shoots but tended to increase root disease severity. *T. roseum* treatment did not affect the controls.

Seed health tests (Sherpa)

As with Camargue, recovery rates were greater for *F. culmorum* and *F. sambucinum*, intermediate with *F. avenaceum* and *F. graminearum* and lowest with *F. poae, F. nivale* and *T. roseum* (Table 5.11). Surface sterilization significantly reduced recovery only with *F. graminearum* and *T. roseum.*

On average pre-treatment with *T. roseum* significantly reduced seed colonization by the inoculated fungal species but post-inoculation treatment had no effect relative to no *T. roseum* treatment. A variable effect of *T. roseum* on the recovery rates of the different fungal species was observed (Table 5.12). No significant differences were observed in the recovery rates of *F. culmorum* and the controls with either of the *T. roseum* treatments.

FIGURE 5.5a. Disease severity index (%) of roots of barley cv. Camargue in relation to fungal species, inoculum treatment and time of inoculation.

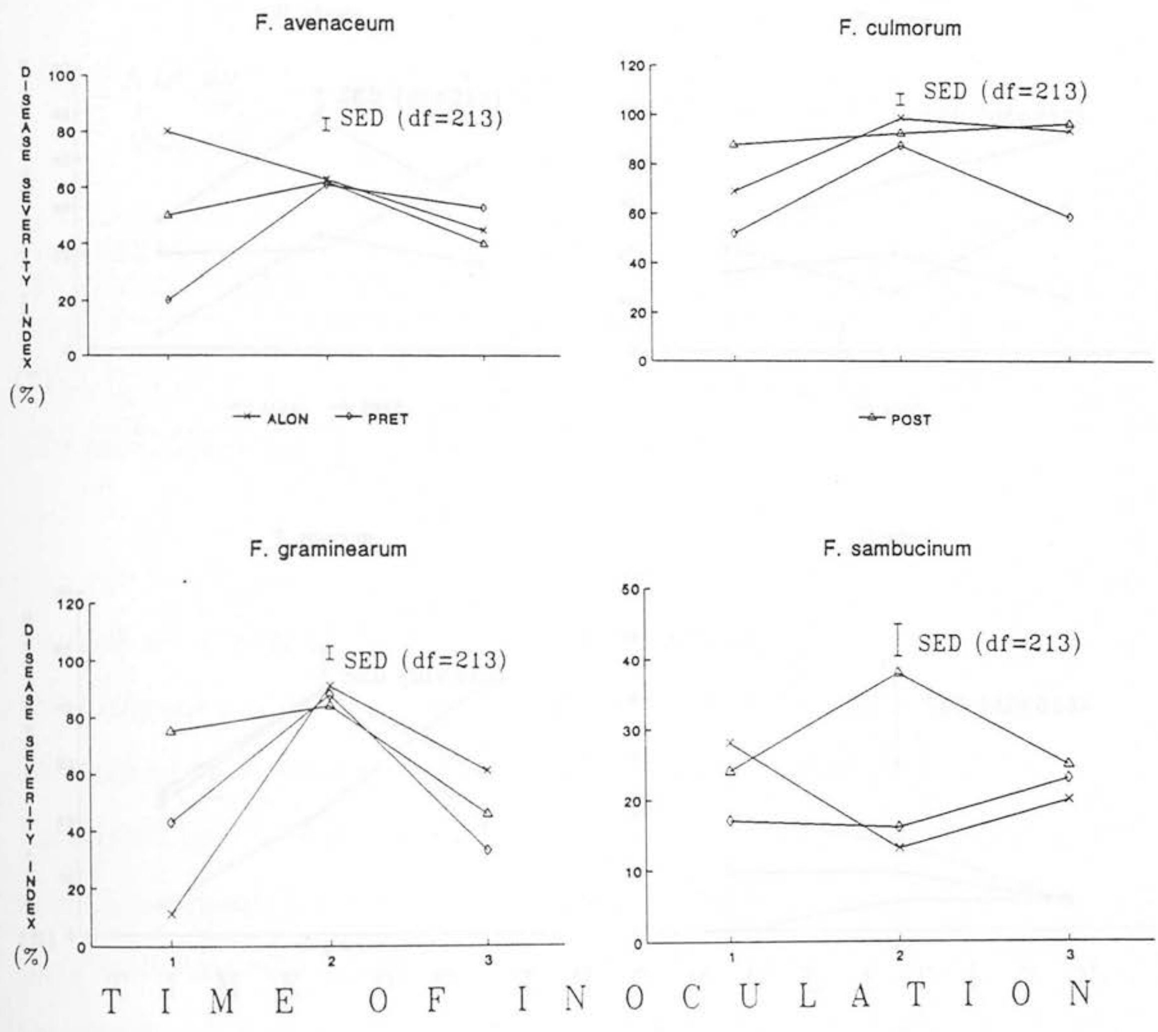


FIGURE 5.5b. Disease severity index (%) of roots of barley cv. Camargue in relation to fungal species, inoculum treatment and time of inoculation.

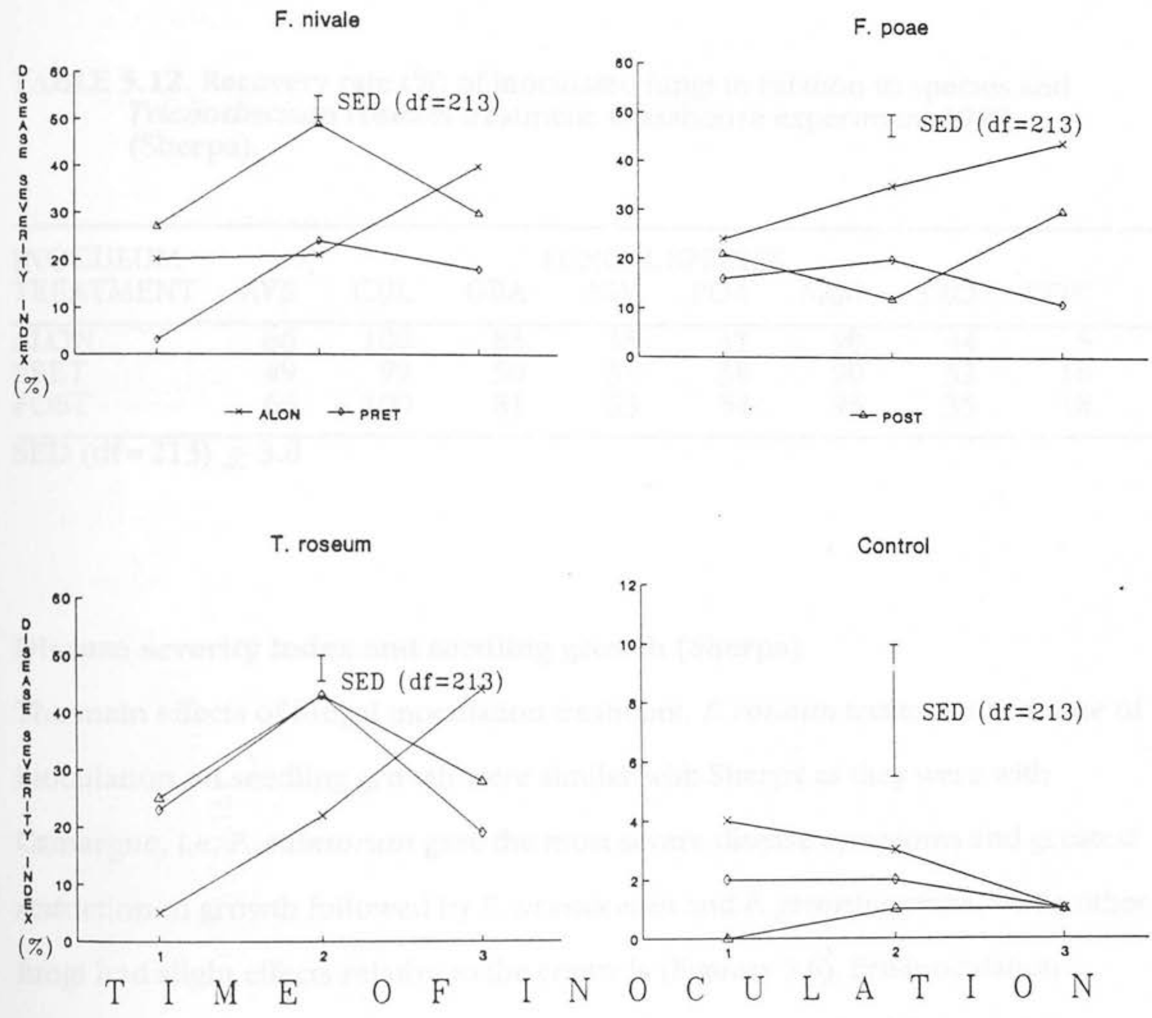


Table 5.11. Recovery rate of inoculated *Fusarium* in relation to species and seed sterilization. Glasshouse experiment-1989 (Sherpa).

SEED TREATMENT	FUNGAL SPECIES AVE	CUL	GRA	NIV	POA	SAM	TRO	CON
Sterilized	60	100	68	32	46	91	28	11
Unsterilized	60	100	75	34	48	96	46	15

SED (df=314) ± 3.1

TABLE 5.12. Recovery rate (%) of inoculated fungi in relation to species and *Trichothecium roseum* treatment. Glasshouse experiment-1989 (Sherpa).

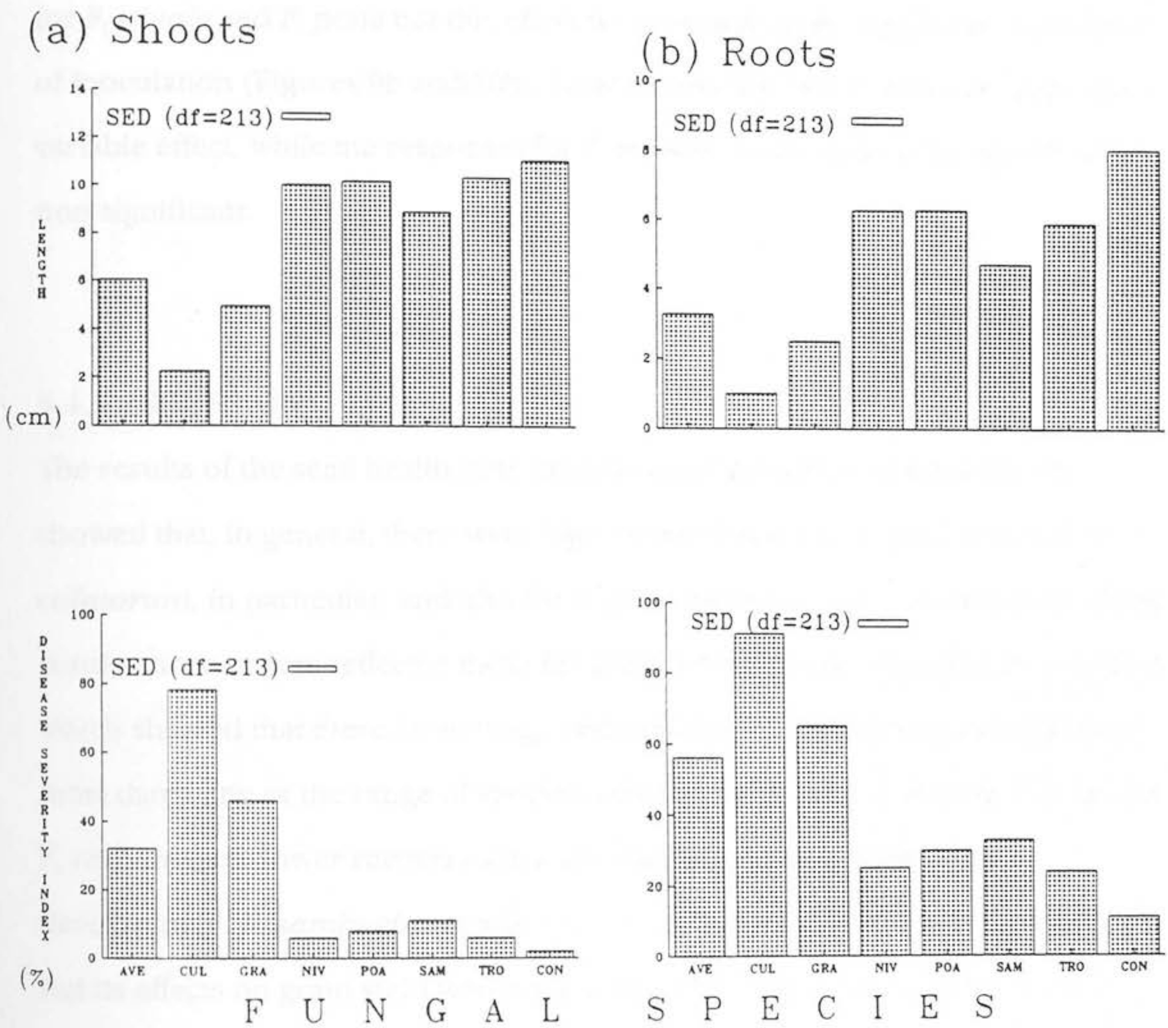
INOCULUM TREATMENT	FUNGAL SPECIES AVE	CUL	GRA	NIV	POA	SAM	TRO	CON
ALON	66	100	83	35	47	99	44	5
PRET	49	99	50	31	38	90	32	16
POST	66	100	81	33	54	93	35	18

SED (df=213) ± 3.8

Disease severity index and seedling growth (Sherpa)

The main effects of fungal inoculation treatment, *T. roseum* treatment and time of inoculation on seedling growth were similar with Sherpa as they were with Camargue, i.e. *F. culmorum* gave the most severe disease symptoms and greatest reduction in growth followed by *F. avenaceum* and *F. graminearum*, while other fungi had slight effects relative to the controls (Figures 5.6). Pre-inoculation treatment with *T. roseum* reduced adverse effects on growth while inoculation at

FIGURE 5.6. Disease severity index (%) and length (cm) of shoots and roots of barley cv. Sherpa in relation to fungal species (averaged for inoculum treatment and time of inoculation).



mid-anthesis gave the highest disease severity indices and greatest reductions in shoot and root growth (Figures 5.7 and 5.8). However, as with Camargue, there were significant interactions between these factors and these are illustrated in Figures 5.9 and 5.10. for disease severity indices. Treatment with *T. roseum* 1 week before inoculation gave below average indices for all times of inoculation of *F. culmorum* but with *F. avenaceum*, *F. graminearum* and *F. sambucinum* beneficial effects were largely evident with early inoculation but not consistently at other times (Figures 5.9a and 5.10a). With post inoculation *T. roseum* treatment effects were variable depending upon fungal species and time of inoculation treatment. Pre-inoculation *T. roseum* treatment generally reduced disease severity for *F. nivale* and *F. poae* but this effect was not statistically significant at all times of inoculation (Figures 5.9b and 5.10b). Later treatments with *T. roseum* again had a variable effect, while the responses for *T. roseum* inoculation and controls were non-significant.

5.4. DISCUSSION

The results of the seed health tests carried out in this series of experiments showed that, in general, there were high recovery rates of inoculated fungi for *F. culmorum*, in particular, and also for *F. graminearum* and *F. avenaceum*. These results more or less reflected those for grain development in the previous section which showed that these three fungi, and especially *F. culmorum*, ranked as the most damaging of the range of species included in the tests. *F. nivale*, *F. poae* and *T. roseum* gave lower recovery rates and had little influence on grain development. *F. sambucinum* was unusual in that it showed a high recovery rate but its effects on grain yield were very slight. This fungus has been previously

FIGURE 5.7. Disease severity index(%) and length (cm) of shoots and roots of barley cv. Sherpa in relation to inoculum treatment (averaged for fungal species and time of inoculation)

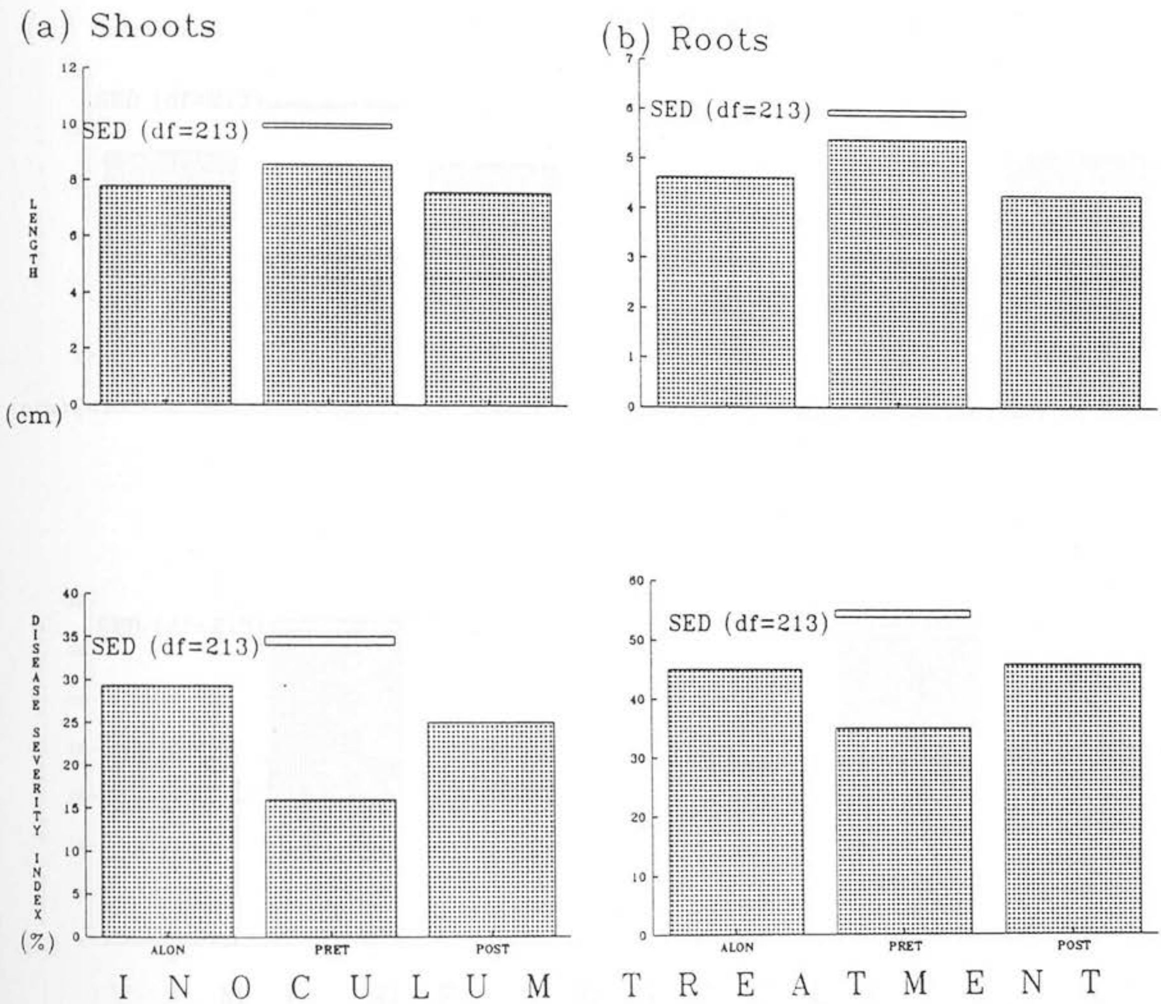


FIGURE 5.8. Disease severity index (%) and length (cm) of shoots and roots of barley cv. Sherpa in relation to time of inoculation (averaged for fungal species and inoculum treatment).

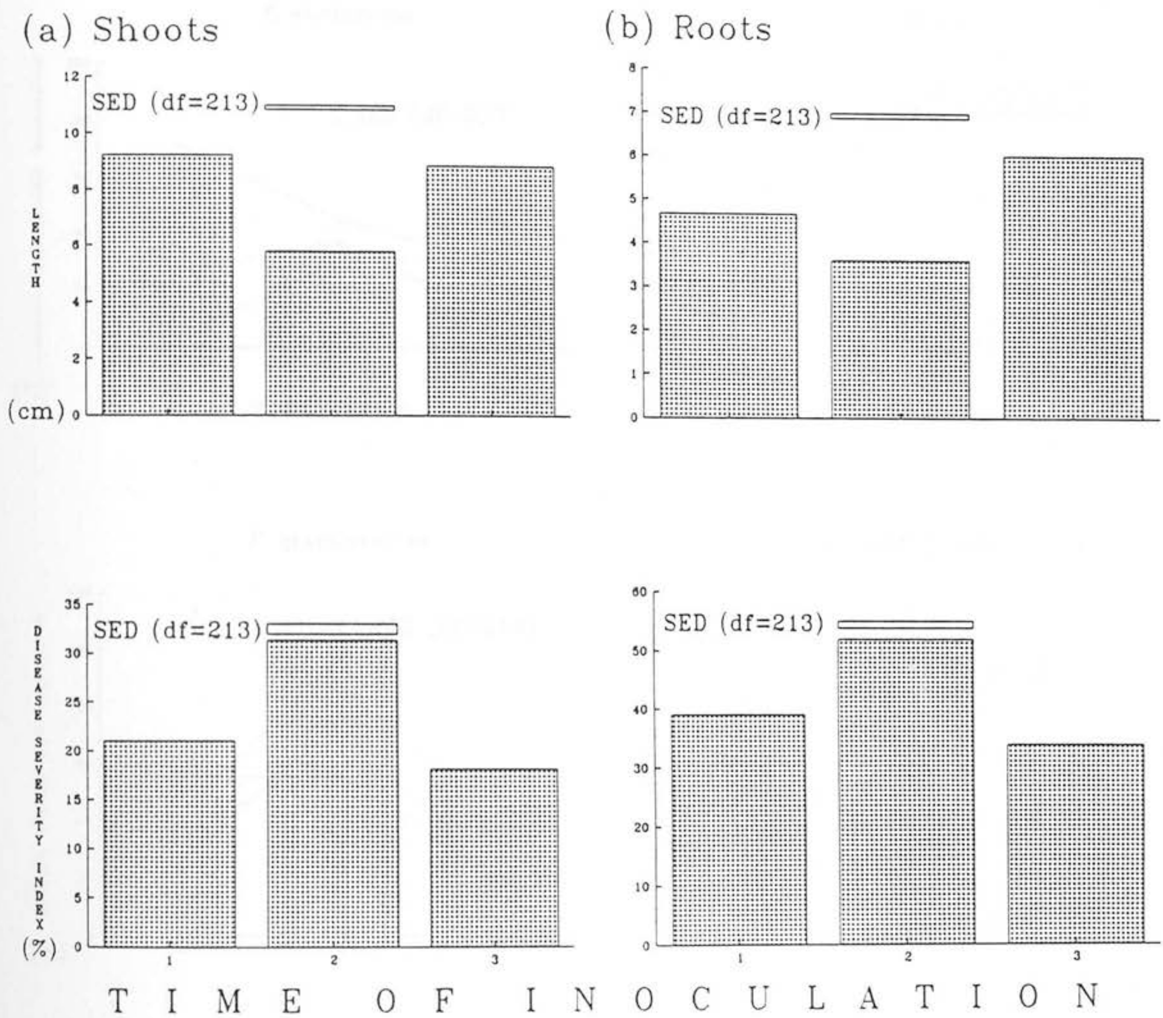


FIGURE 5.9a. Disease severity index (%) of shoots of barley cv. Sherpa in relation to fungal species, inoculum treatment and time of inoculation.

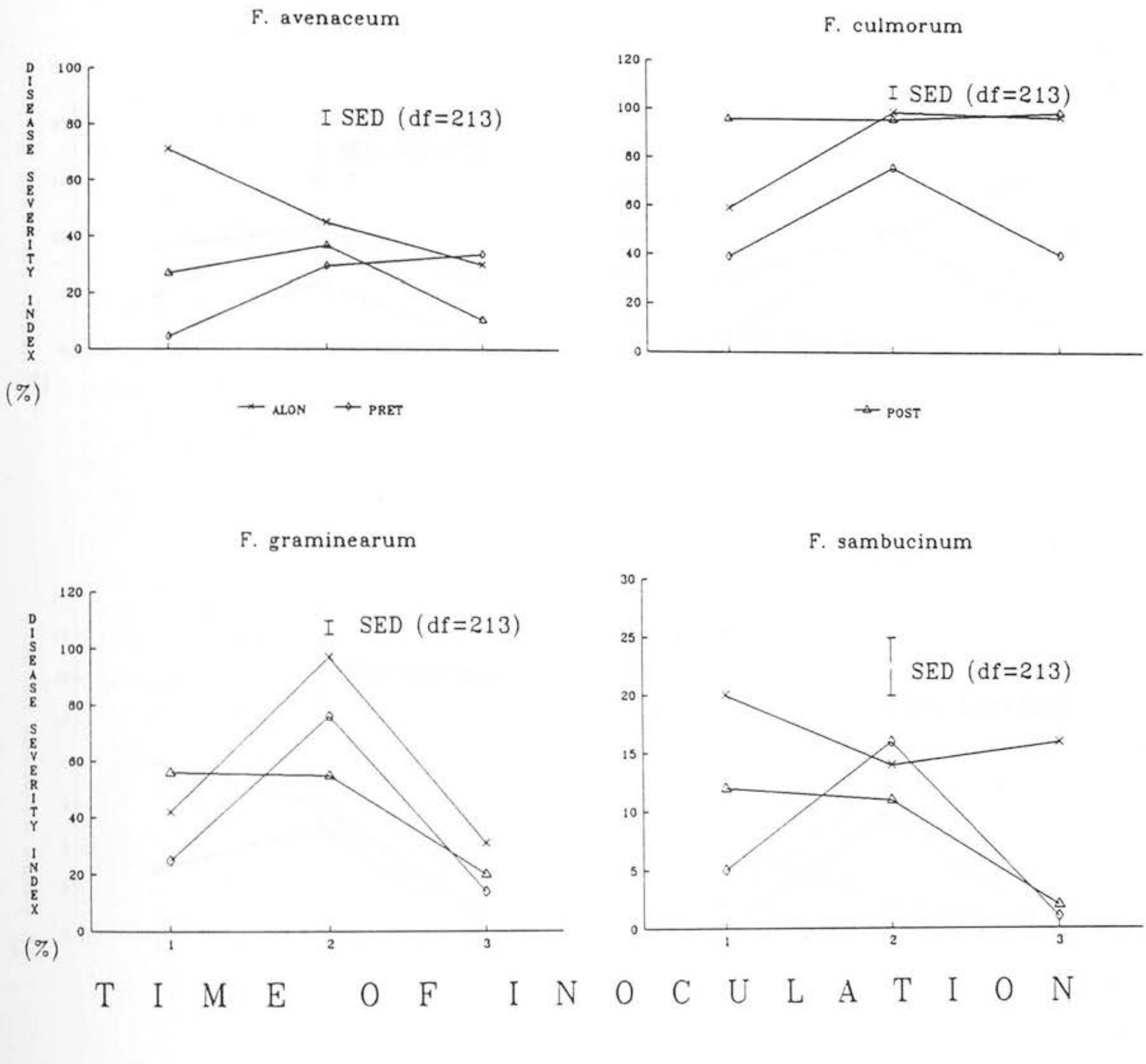


FIGURE 5.9b. Disease severity index (%) of shoots of barley cv. Sherpa in relation to fungal species, inoculum treatment and time of inoculation.

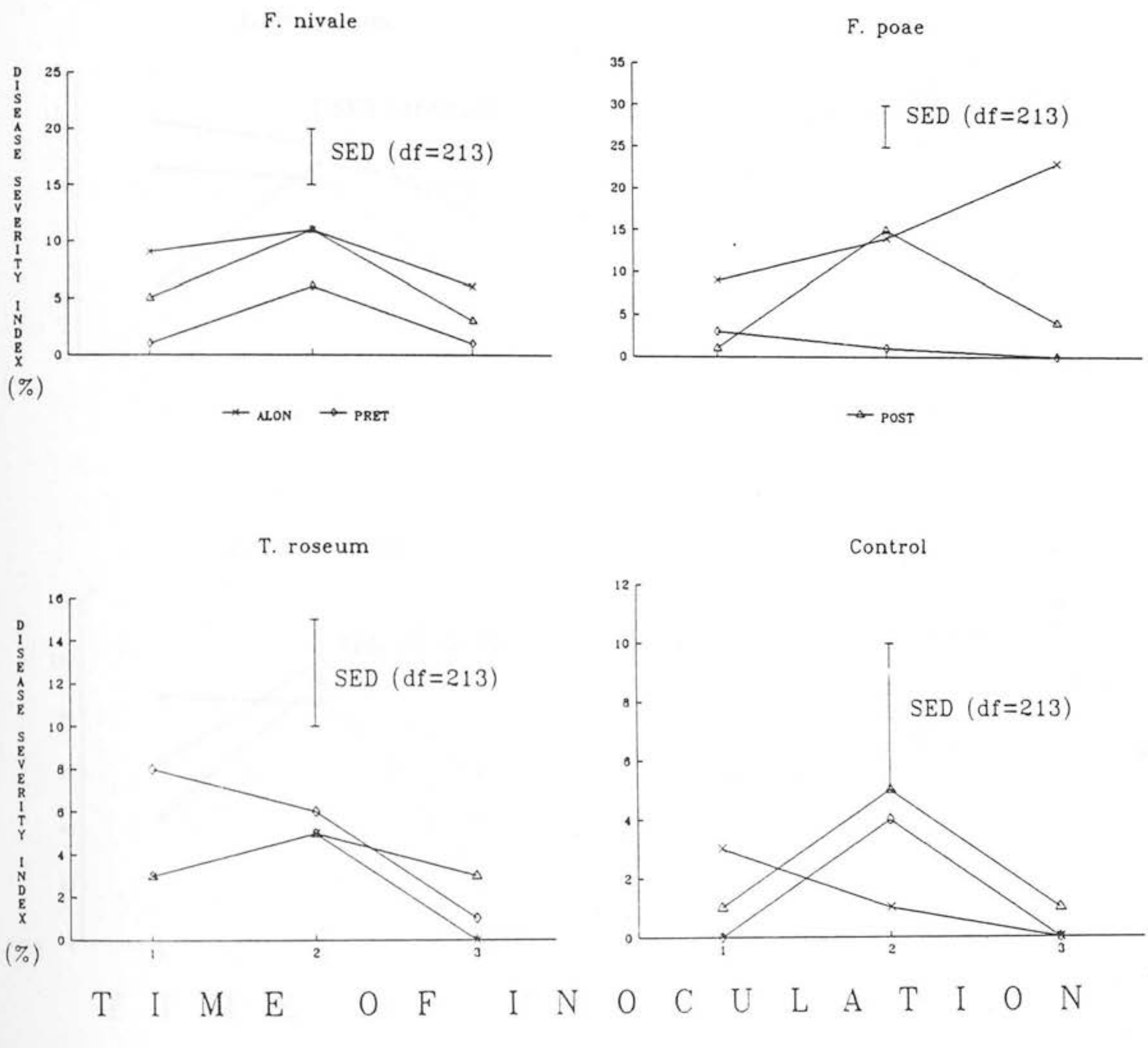


FIGURE 5.10a. Disease severity index (%) of roots of barley cv. Sherpa in relation to fungal species, inoculum treatment and time of inoculation.

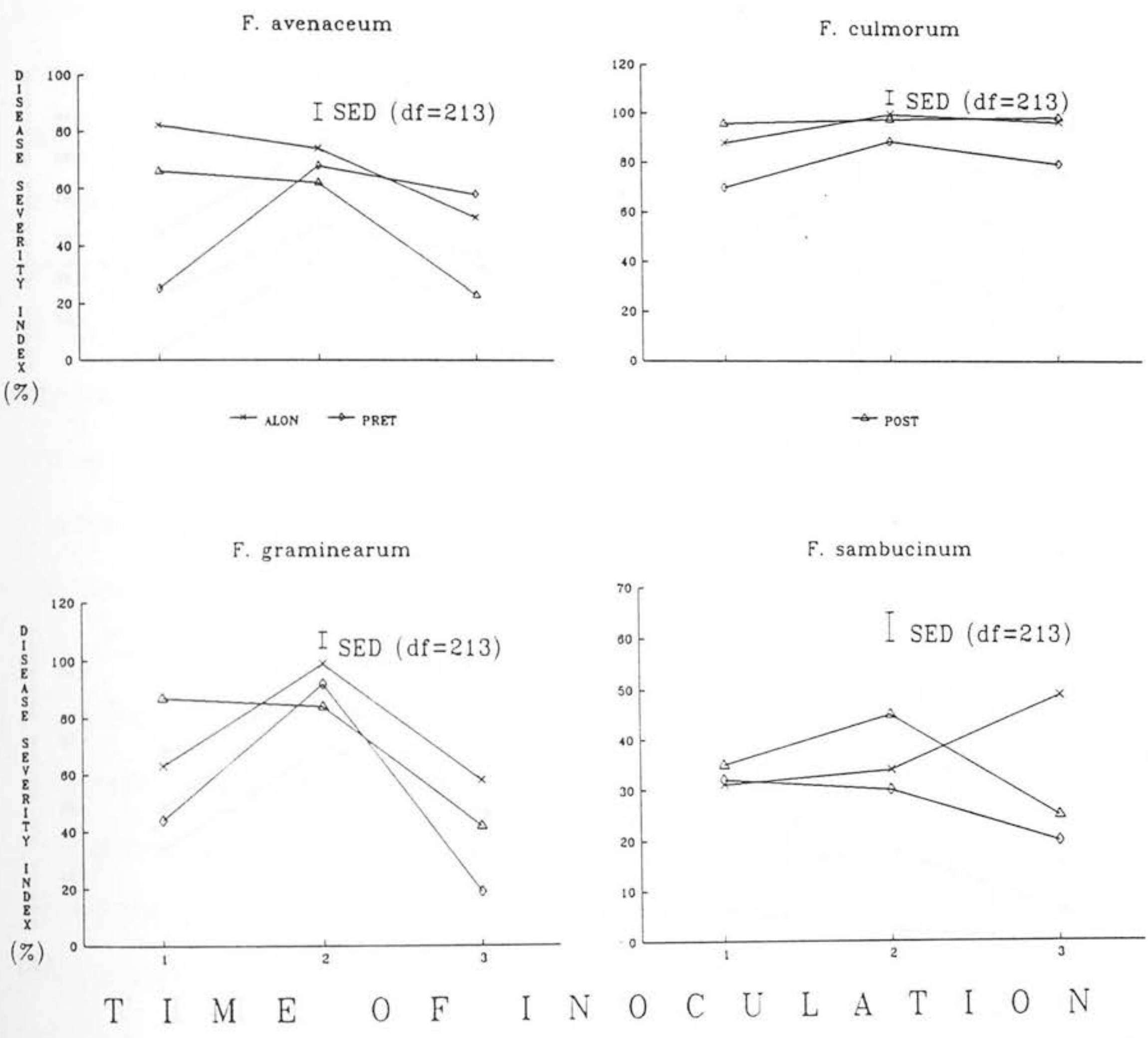
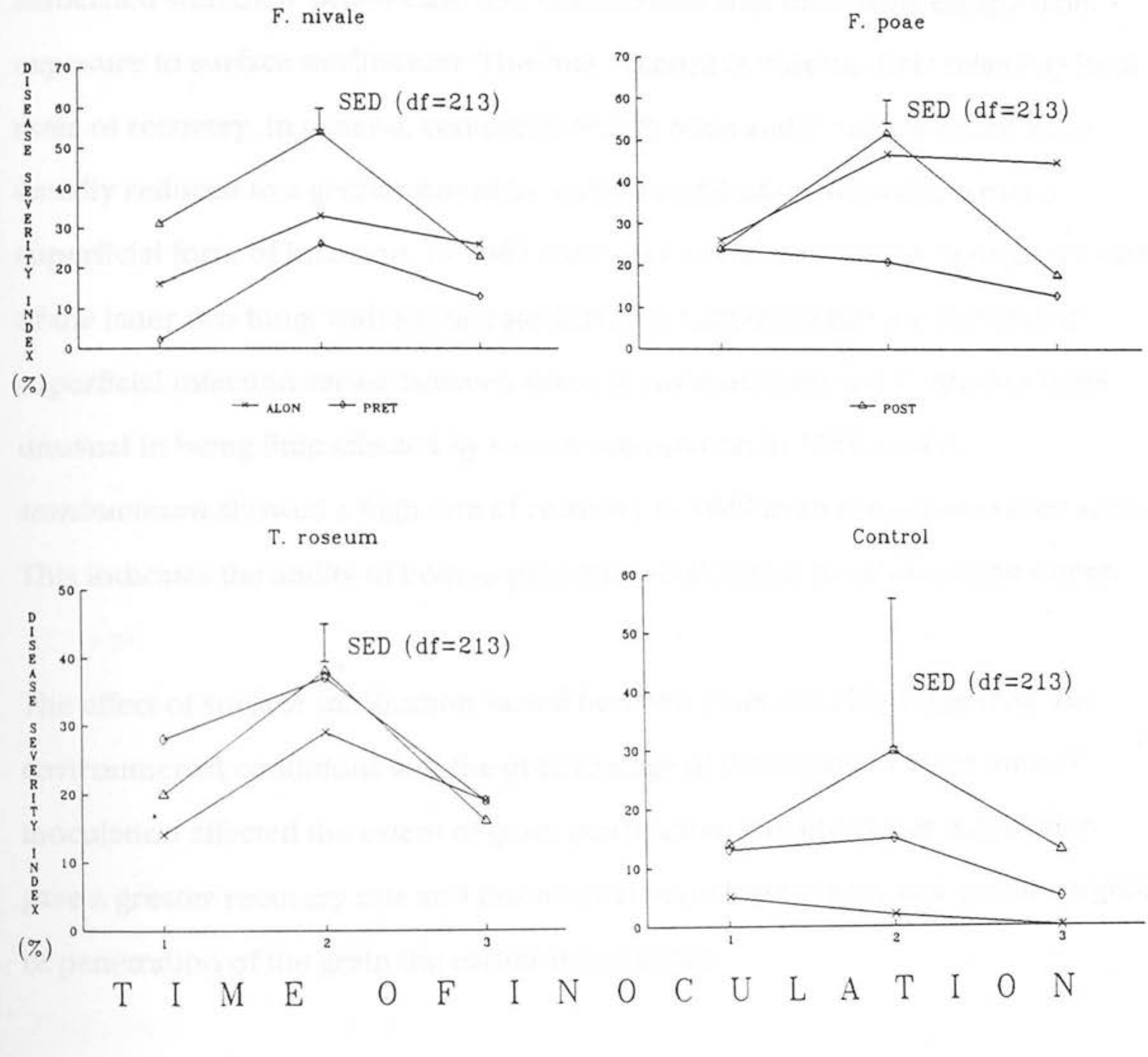


FIGURE 5.10b. Disease severity index (%) of roots of barley cv. Sherpa in relation to fungal species, inoculum treatment and time of inoculation.



reported as a seed-borne pathogen but at a very low incidence (Wilcoxson *et al.*, 1988).

It was observed that seed sterilization significantly reduced recovery rates on average, but the effect varied with different fungi. Thus, in the case of *F. culmorum* seed sterilization tended to have little if any effect on frequency of isolation, indicating the deep-seated nature of seed infection with this species. In keeping with this results, *F. culmorum* was notable in the previous section for its adverse effect on grain size. *F. avenaceum* and *F. graminearum* recovery rates were only moderately affected by seed sterilization and this again may be associated with their penetration into grain tissues and, thus, their escape from exposure to surface sterilization. This may account in part for their relatively high rates of recovery, in general, compared with *F. poae* and *F. nivale* which were usually reduced to a greater extent by surface sterilization, implying a more superficial form of infection. In 1989 there was less of a reduction in recovery rate of the latter two fungi with surface sterilization, suggesting that the survival of superficial infection varied between years. *F. sambucinum* and *T. roseum* were unusual in being little affected by surface sterilization in 1988, and *F. sambucinum* showed a high rate of recovery in 1989 from surface sterilized seed. This indicates the ability of both to penetrate seed tissues to at least some extent.

The effect of surface sterilization varied between years possibly suggesting that environmental conditions and the precise stage of development at the time of inoculation affected the extent of grain penetration. Usually earlier inoculation gave a greater recovery rate and this may relate, at least in part, to a greater degree of penetration of the grain the earlier it is infected.

Seed germination and seedling growth were affected by inoculation of ears with all of the fungi tested. In general it could be stated that planting of *Fusarium*-infected seed may result in weak seedlings, giving rise to poor stands as it has been found by Uoti (1979) and Mesterhazy (1974). However, the effects were clearly most severe, and disease symptoms most obvious in the case of *F. culmorum*. This may be attributable to the direct attack of seed and seedling by this fungus, and also to its effect on grain size, which is known to be linked to seed vigour. Mesterhazy (1977) found that from nine different *Fusarium* species tested, *F. culmorum*, and *F. graminearum* were the most pathogenic species when inoculated to the ears at different flowering stages these two species significantly reduced shoot length as a result of heavy seed infection. *F. avenaceum* and *F. graminearum* also showed, in the present work, marked pathogenic effects on seed and seedling performance in keeping with their observed effects on grain yield (Section 4) and extent of carry-over on seed. However, other fungi used for inoculation i.e. *F. nivale, F. poae, F. sambucinum* and *T. roseum* showed some reduction in seed vigour and seedling performance, indicating that although colonization of ears by these species may produce no obvious effects on the grain they may still be of economic importance in the adverse effects they have on seed performance. It should be noted, however, that inoculation dosage rates were higher in these experiments than would be normally expected in field conditions. In addition to their pathogenic effects, a mycotoxin risk has been associated with at least some of these fungi.

Observations on the position of *F. nivale* as a pathogen have been conflicting. *F. nivale* has been reported as the main cause of seedling blight in cereals (Hewett, 1983, Rennie & Richardson, 1983). Its role, however, as a seedling pathogen is not clear as many others have indicated no or very little pathogenicity towards cereals (Millar & Colhoun, 1969b; Perry, 1986). The results of the present work would categorize it as a weak pathogen of cereals, but to what extent this relates to temperature conditions of the experiments is uncertain. With regard to *T. roseum*, this fungus could also be classed as a weak pathogen of cereals. The fungus has been reported as a cause of seedling blight and seed decay in different cereals including wheat and maize (Desai & Siddaramaiah, 1980; Sing *et al.*, 1985; Vakili, 1985) and of other plant species such as common beans (Tu, 1985).

With regard to cultivar response to ear inoculation with the different fungal species, well defined trend was observed. In some instances certain cereal species or cultivars seemed more susceptible to particular fungi than others, but the results were not consistent. Martin & Johnston (1982) observed a reduced seedling performance of barley followed by wheat, while oats appeared to have some tolerance to the detrimental effects of *Fusarium* species: this finding was not borne out in the present work. Where more detailed studies have been carried out, some resistance to *F. culmorum* within wheat cultivars has been found (Mesterhazy, 1977; 1978; Parry, *et al.* 1984).

When testing the performance of seed obtained from the ear inoculation experiment in 1989, it was observed that there was a significant effect of applying *T. roseum* to ears 1 week before inoculation with different *Fusarium* species in reducing any pathogenic effects on barley seed and seedlings of the inoculum. Its tendency, however, did not seemed to be consistent for all fungi and all times of inoculation. It was observed [illegible] most regularly to reduce effects of *F. culmorum*. This may be due to the fact That once *T. roseum* was established, *F. culmorum* had to compete with it or, as explained in Section 4, that it interfered with stimulatory factors.

However, the results as a whole were too unpredictable to suggest that *T. roseum* may have a role as a biological control agent. Moreover, *T. roseum* itself had pathogenic effects, although minor, on cereal grain.

SECTION 6

THE EFFECT OF CEREALS SEED AND SOIL INOCULATION WITH DIFFERENT FUNGAL SPECIES ON SEED AND SEEDLING PERFORMANCE

6.1 INTRODUCTION

In the previous section the effect of ear inoculation at different stages of development on the subsequent performance of seed and seedlings has been studied. In this section, artificial seed and soil inoculations with different *Fusarium* species, alone or in association with other fungi isolated from the field trials, are assessed: a particular interest was the effect of *T. roseum* on the seedling development.

Among the factors in the environment which determine the progress of infection by pathogenic fungi is their interaction with other microorganisms. Antagonism between microorganisms is a well recognized phenomenon and is particularly intensive in the soil around plant roots, i.e. the rhizosphere, but may also be evident on aerial shoot surfaces, i.e. the phyllosphere. Antagonism may assume different forms namely antibiosis, parasitism and competition.

It has been found that specialized hyperparasites, such as *Darluca filum* and *Ampelomyces quisqualis* affect plant pathogens in two main ways, namely by penetration of fungal tissues and production of metabolic substances which result in destruction, by lysis, of spores, sori, or hyphae, and by displacement of tissues of the pathogen by the hyperparasite either within pustules or by the formation of crusts of mycelium which overlie fruiting structures. A less specialized hyperparasitic relationship has been shown by *Trichothecium roseum* which restricts development of other fungi, including *Rhizoctonia solani* (Chand & Logan, 1984; Logan, Little & Cooke, 1984), *F. moniliforme, Venturia inaequalis* and *Pythium* spp. (Froto & Bailey de Ibarra, 1983), by hyphal interactions involving coiling or penetration.

Competition usually involves rivalry for nutrients and growth factors rarely for space and oxygen. Lindsey (1965) demonstrated that *Fusarium. roseum* , a classical example of a soil-inhabitating fungus living indefinitely as a saprophyte (Garrett, 1970), competed more effectively than *F. solani* f. *solani* for substrates in soil microbiological sampling tubes. Lindsey systematically eliminated linear growth rate, antibiotic production, and fungistatic substances as significant factors in the superior competitive saprophytic ability of *F. roseum.* The dominant factor was the ability of this fungus to compete for soil nitrogen. Lai & Bruehl (1968), when testing the effect of time of arrival on the establishment of some soil-borne fungi, found a strong competitive antagonism between *Cephalosporium gramineum* and *F. culmorum*, and *Trichoderma* species and *F. culmorum* in wheat straws buried in soil. They stated that the possession of the substrate was markedly important in establishing dominance in the substrate. Similar findings were obtained by Warren & Kommedahl (1973) who reported that on oat residues, *F. roseum* was the most prevalent followed by *F. oxysporum* and *F. solani*. *F. nivale* and *F. graminearum*, on the other hand, have been reported as poor competitors in the soil, presumably due to the lack of chlamydospores (Al-Hashimi & Perry, 1986). Their success to pass from one year to another apparently depends on ability to infect fresh material.

Seeds frequently carry an abundant and diverse microflora, and the ways in which the activity of this flora may influence the development of disease caused by soil- or seed-borne pathogens has been, in the last two decades, investigated by artificially inoculating seed and/or soil with different fungi. According to Noble (1971) not all seed-borne inoculum is able to survive to infect seedlings or soil and the antibiosis of organisms on the seed itself or in the soil is one of the very important reasons for this lack of survival. A classic example is that Tveit & Wood

(1955) who observed that although oat seed was often infected by *F. nivale*, this fungus fail to cause seedling blight due to the antagonistic effects of some saprophytic fungi such as *Chaetomium* spp. which were also present on the seed. Similarly, *Epicoccum* spp. produced antibiotic substances. These two workers reported that certain isolates of *Chaetomium cochliodes* and *C. globosum* drastically reduced the effect of *F. nivale* on the germination of oats. Substantial control of this fungus was also obtained when infected seed was sown in soil to which cultures of *C. cochliodes* had been added in advance. Bateman (1979), found that when inoculating seeds with a mixture of saprophytes and seed-borne *F. nivale*, *Alternaria* was the only fungus which significantly reduced the severity of infection by *F. nivale*. This, however, was inconsistent apparently due to a variation in isolates. Two isolates of *Epicoccum* generally reduced the severity of seedling disease (Ponchet, 1966). Biological control of *F. nivale* on wheat by the soil microflora was demonstrated by Millar & Colhoun (1969b) when inoculated seed was used. This inhibition of disease development occurred in a fairly high proportion of the cereal growing soils examined. Control was not, however, achieved when seed naturally contaminated with *F. nivale* was employed, and so they concluded that only infections resulting from surface inoculum on seeds was controlled by the soil microflora. Of a number of organisms isolated from soils showing inhibitory effects to disease development, isolates referred to the *Gliocladium roseum* group caused most effective control.

The production of antibiotics is a well recognized way of antagonism. Of the filamentous fungi which inhabit leaf surfaces, species of *Alternaria, Botrytis* and *T. roseum* have been reported to produce antibiotics. Dickinson & Skidmore (1976), reported that *Botrytis cinerea* produces a number of antibiotic substances which antagonized other fungi on plant surfaces. However, this fungus has also been reported as a weak parasite of cereal crops as well as causing disease in other species of plants. *T. roseum* has been observed to show antagonism to pathogens through the production of metabolic compounds (Freeman & Morrison, 1949; Freeman, 1955; Beratlief & Tircomnicu, 1979). These last two workers found, from *in vitro* tests that *T. roseum* was able to antagonize *F. graminearum*, acting mainly through its metabolites. The same metabolites, however, may reduce the seed germination, and root and shoot elongation of several crop plants (Girisham, Reddy & Reddy, 1985).

The role of *T. roseum* as an antagonistic agent against fungal plant pathogens, may suggest its possible use as a biological control agent. The fungus, however, has also been implicated as cause of several diseases of plants belonging to different families. *T. roseum* was reported by Sing, Sing & Sing (1985) to cause rot and seedling blight in maize. They found that the fungus was able to cause deep infection, invading the embryo in seeds of this cereal.

In Canada (Tu, 1985), *T. roseum* was found to cause a disease of common bean *(Phaseolus vulgaris)* characterized by the appearance of a powdery mould, which was initially white and eventually turned pink. Tu (1985), reported approximately 15% of the seed harvested from the field were discoloured. When carrying out germination tests the same worker found that only 1% of the diseased seeds were able to germinate: diseased seeds were decayed and covered with a pink mould. When studying the causes of cankers in rose canes, Sweets, Pfleger, Morgan & Mizicko (1982), *T. roseum* was found invading canes of rose.

It is clear that although there is no evidence that *Fusarium* diseases of cereals can at present be prevented by biological control, nevertheless it is important in to appreciate the effects which the seed and soil mycoflora may have upon disease incidence. The aim of this section, therefore, was to assess the effect of some of the fungi most frequently isolated from roots and stems of cereals during the two-year survey of field trials, on the severity of disease caused by *Fusarium* species on seedlings of barley, wheat, oats and triticale.

A further point to these experiments is that *Fusarium* infection may originate from the soil and they, therefore, provide an opportunity to consider a further facet of the pathogenic behaviour of *Fusarium* species in relation to cereal plants.

The experiments are considered under the following headings:-

(a) Studies of the effect of *Trichothecium roseum* inoculated to infected or infested seed of barley with different *Fusarium* species.

(b) Studies of the effect of inoculation of seed and soil with various *Fusarium* species and *T. roseum*.

(c) Seed inoculation of different cereal plants with *T. roseum*.

(d) Studies on the effect of different spore concentrations of *F. culmorum* and *T. roseum* on seedling performance.

(e) Studies of the effect of inoculation of seed of wheat with *Fusarium* species and other fungi on seedling emergence.

6.2 MATERIALS AND METHODS

6.2.1 Experiment 1:

Seeds of barley, cv Golden Promise, were harvested from the ears inoculated with *Fusarium* species as described in Experiment 4.1 were used in this experiment together with a lot of seed free of any previous fungal or chemical treatment. The *Fusarium* species considered were *F. avenaceum, F. culmorum, F. graminearum, F. nivale* and *F. poae. T. roseum* was added to seed infected from ear inoculation or contaminated from seed inoculation with these *Fusarium* species. *T. roseum* was added 1 week before sowing infected seed (Tr-pre). With contaminated seed, *T. roseum* was applied 1 week before inoculation (Tr-pre) and sowing or 1 week after inoculation (Tr-post), at the time of sowing.

Subcultures of the isolates were grown on PSA (poatato-sucrose-agar) and incubated in light for 8 to 10 days at 20°C. *F. nivale* was incubated at 15°C. Spore suspensions of *T. roseum* or *Fusarium* species were made up from the cultures in distilled water in concentration of 500,000 spores/ml. Inoculum of each fungus was applied at the rate of 1 ml to 50 seeds. Each lot was then shaken vigorously to ensure thorough contamination. Controls were set up by treating seeds with *T. roseum* or distilled water. Each fungal treatment was represented by 10 seeds replicated four times in a randomized block designed. Seed was sown in plastic pots filled with compost at an approximate depth of 2.5 centimetres. Percentage of seedling emergence was assessed after 10 days of sowing.

6.2.2 Experiment 2:

This experiment investigated the effect of different *Fusarium* species inoculated to the soil either alone or in association with *T. roseum* on the seedling establishment of the barley cultivar Golden Promise. It was also concerned with the effect of time of soil introduction of *T. roseum* in relation to *Fusarium* species. The same *Fusarium* species were used as in the previous experiment. Two methods of inoculation were used, one inoculating the seed with the same *Fusarium* spore suspensions as described previously (6.2.1) and the other inoculating the soil. With seed inoculation *T. roseum* was applied 2 weeks before, at the same time or 2 weeks after *Fusarium* inoculation. Each treatment was represented by 10 seeds replicated four times in a completely randomized block design. Plastic pots were filled with fresh compost mixed with the inoculum, which consisted of one of the *Fusarium* species either with or without *T. roseum*. For soil inoculation this fungus was added to the soil at the time of the *Fusarium* species introduction, 2 weeks before or 2 weeks after. To prepare the inoculum four subcultures of the particular fungus were liquidized for about 1 minute and mixed thoroughly with the given volume of soil (0.003 m^3). Agar with no fungal species was added to the control pots. Seed was sown at an approximate depth of 2.5 cm 1 or 15 days after inoculation. The seedlings were grown in a glasshouse for about 10 days and then assessed for the percentage of emerged seeds.

6.2.3 Experiment 3.

This experiment investigated the effect of *T. roseum* on the germination of several cereal cultivars of cereals as well as the effect of spore concentration of this fungus on the seed germination of the wheat cv. Dollar.

Spore suspensions (500,000/ml) of *T. roseum* were inoculated to the seeds of cultivars of barley, Golf and Gerbel; wheat, Avalon and Apostle; oats, Trafalgar and

Avalanche; and triticale, cv. Lasko. Controls had been suspended in water. 25 seeds were placed on moist paper towels replicated four times. Seeds were incubated at 20-23^{o}C for about 7 days and then the percentages of seed germination failure and abnormal seedlings were assessed.

6.2.4 Experiment 4:

Seeds of wheat cv. Dollar without any other pathogen were inoculated with different combinations of spores of *F. culmorum* (cu) and *T. roseum* (tr) as indicated in the results section. These two fungi were grown on PDA for about 10 days under similar conditions as in previous experiments. The different mixtures were inoculated to the seed 24 hours before placing on paper towels and the percentages of ungerminated and brown seedlings were recorded.

6.2.5 Experiment 5:

Barley cv. Golden Promise without any previous chemical seed treatment was used. Isolates of species *Fusarium, F. avenaceum, F. culmorum, F. graminearum, F. nivale* and *F. poae* and of other fungi, *Alternaria, Penicillium* sp. (PEN1 and PEN2) and *Botrytis*, were grown on PDA and subcultures of these were used for seed inoculation. Spore suspensions in water were used to inoculate the seed as in previous experiments with either of the two *Penicillia, Alternaria* or *Botrytis* applied 1 week before the respective *Fusarium* species. The inoculum of each fungus was applied at the rate of 1 ml of spore suspension (500,000/ml) to 40 seeds and then shaken vigorously to ensure thorough contamination. Controls were treated with distilled water only. Four replicates represented by 10 seeds were used. Inoculated seeds were sown in plastic pots and kept in a glasshouse for about 10 days and then assessed for the percentage of emerged seedlings.

The analyses of data from the various experiments are summarized in Appendices XIII-XVII.

6.3 RESULTS

6.3.1 Experiment 1: Studies of the effect of *T. roseum* inoculated to infected or infested seed of barley with different *Fusarium* species.

In considering the averaged effects of the different *Fusarium* species, from Figure 6.1 it is seen that *F. culmorum* caused the greatest reduction in the percentage of seedling emergence, *F. avenaceum* and *F. graminearum* were intermediate while the inoculation of seed with *F. nivale* and *F. poae* did not affect seedling emergence compared with control plants. The results for inoculation treatment show that ear inoculation gave the poorer emergence, especially in the presence of *T. roseum*, while pre-treatment with *T. roseum* from seed inoculation gave the highest emergence rate (Figure 6.2).

With regard to specific inoculum treatment, it was observed that seed from ear inoculation with *F. avenaceum, F. culmorum* and *F. graminearum* gave a very poor percentage emergence and its performance was even poorer from inoculation of seed with *T. roseum* (Table 6.1). When *T. roseum* was inoculated to the seed 1 week before the inoculation of *Fusarium* species the percentage of seedling emergence was improved but no statistical differences were observed between the inoculation of *T. roseum* 1 week after *Fusarium* species and no *Fusarium* species: when comparing the results for the *Fusarium* species

TABLE 6.1. The effect of inoculation of barley seed cv. Golden Promise with different *Fusarium* species with (Tr) or without (0) *T. roseum* on seedling emergence (%).

Fusarium species	Seed from ear inoculation		Seed inoculated at the time of sowing		
	Tr-POST	0	Tr-POST	Tr-PRE	0
F. avenaceum	13	18	85	83	55
F. culmorum	0	3	68	85	25
F. graminearum	10	25	73	90	78
F. nivale	63	90	63	93	73
F. poae	50	83	75	88	83
Control	35	78	83	93	95

SED (df=159) $\pm$ 4.6

FIGURE 6.1. Seedling emergence (%) of barley cv. Golden Promise in relation to *Fusarium* inoculation (averaged for seed inoculation treatment).

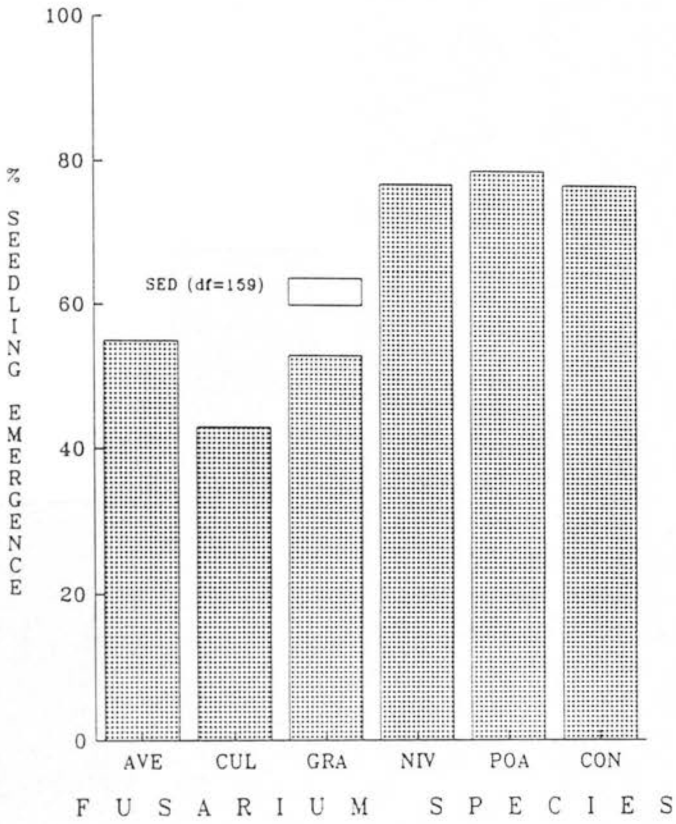
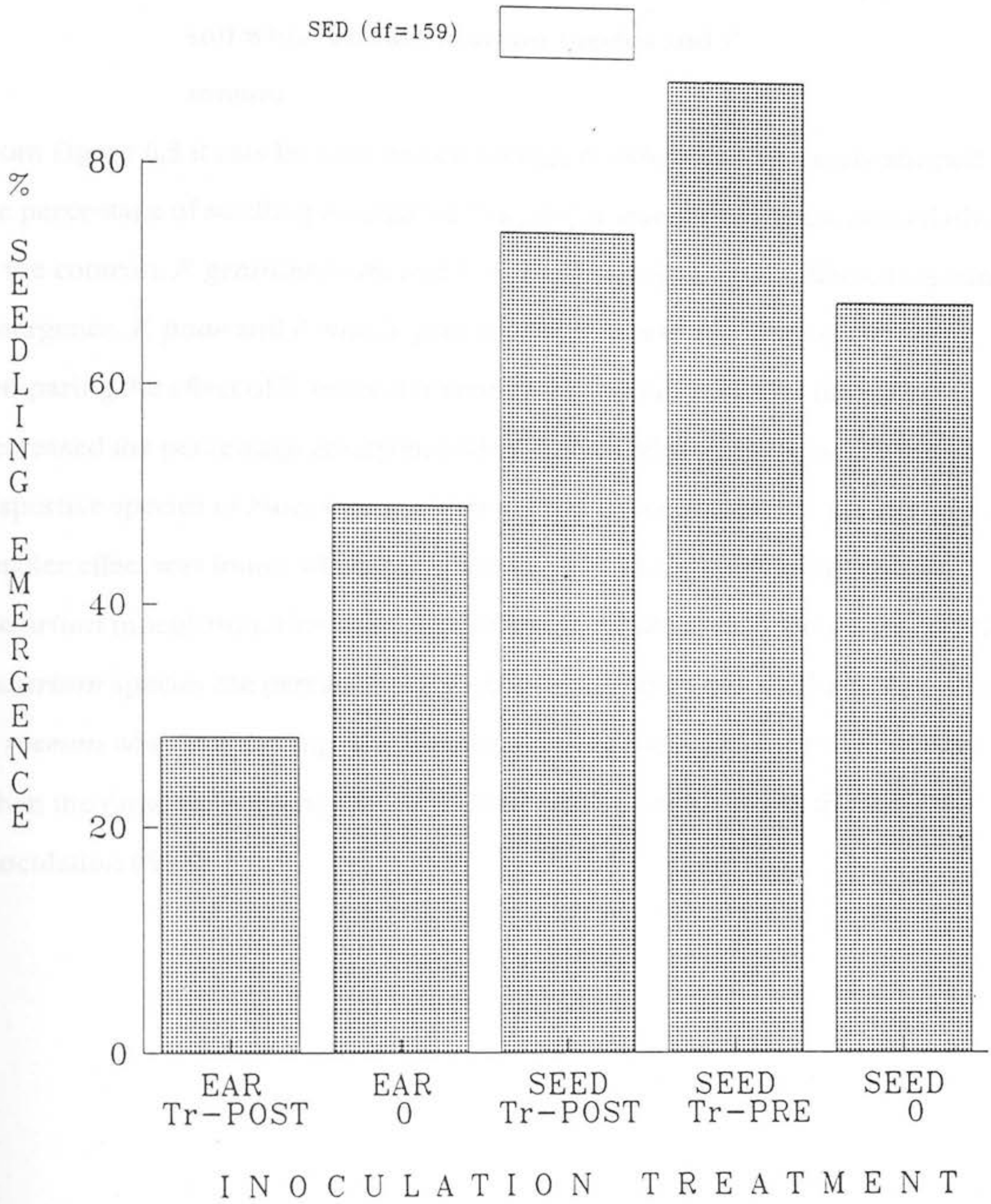


FIGURE 6.2. Seedling emergence (%) of barley cv. Golden Promise in relation to seed inoculation treatment (averaged for *Fusarium* species).



inoculated either before or after with *T. roseum* it was found that with the exception of *F. avenaceum*, the adverse effect of *Fusarium* species on the seedling emergence was less with pre-inoculation treatment for each of the species (Table 6.1).

6.3.2 Experiment 2: Studies of the effect of inoculation of barley seed and soil with various *Fusarium* species and *T. roseum.*

From Figure 6.3 it may be seen that on average *F. culmorum* adversely affected the percentage of seedling emergence to a greater extent (44% reduction relative to the control). *F. graminearum* and *F. avenaceum* moderately effected seedling emergence. *F. poae* and *F. nivale* gave similar results to the controls. In comparing the effect of *T. roseum* treatment it was found that this fungus decreased the percentage emergence when it was added 2 weeks before the respective species of *Fusarium* to either the soil or seed (Figure 6.4, Plate 6.1). A smaller effect was found when *T. roseum* was inoculated 2 weeks later than *Fusarium* inoculation. However, when it was inoculated at the same time with the *Fusarium* species the percentage of seedling emergence was similar to that when *T. roseum* was absent. A higher percentage in seedling emergence was obtained when the fungi were inoculated to the seed (80%) compared with the soil inoculation (66%).

FIGURE 6.3. Seedling emergence (%) of barley cv. Golden Promise in relation to *Fusarium* inoculation (averaged for *T. roseum* treatment and inoculated substrate).

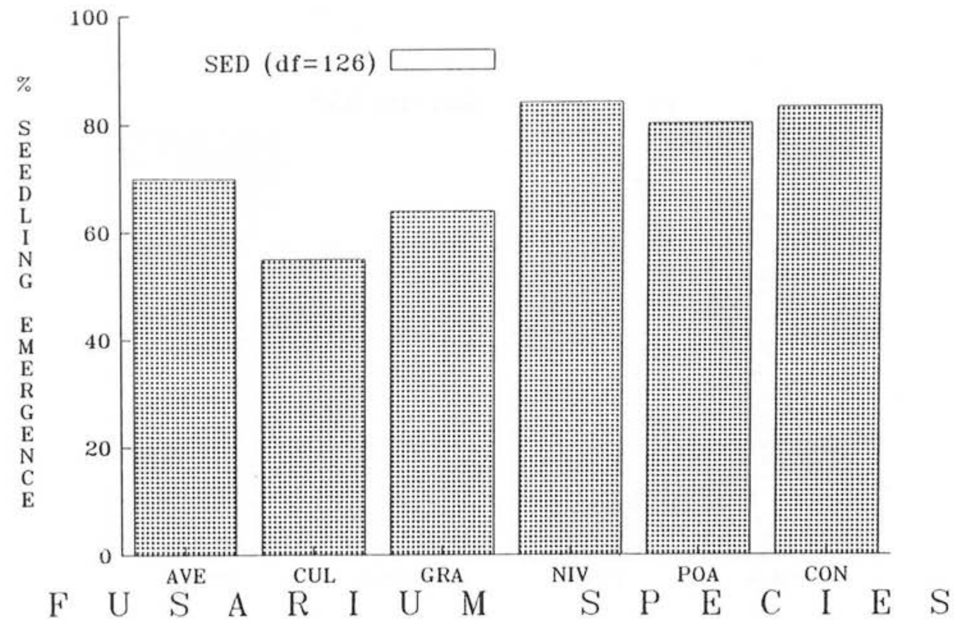
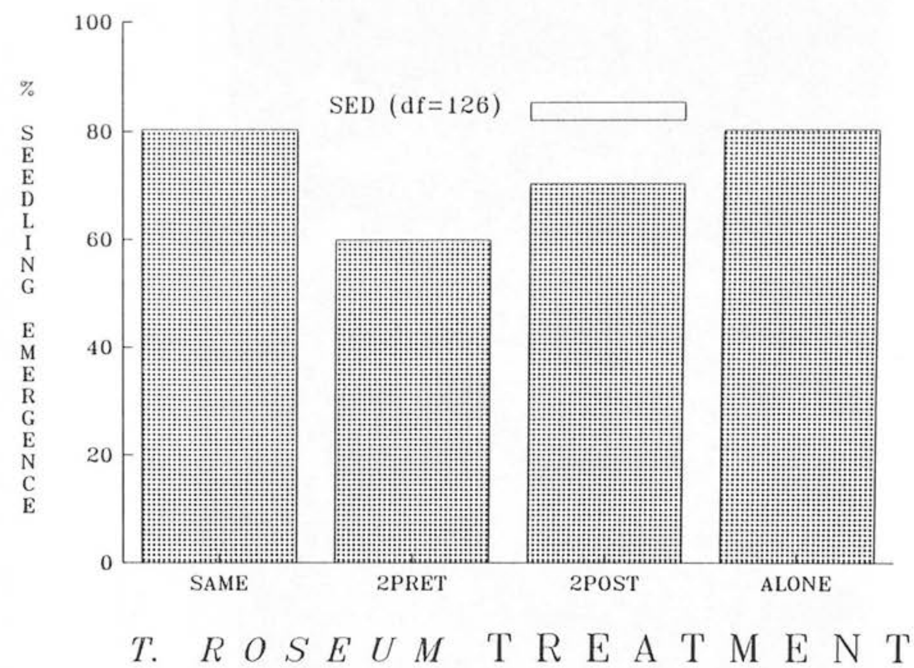


FIGURE. 6.4. Seedling emergence (%) of barley cv. Golden Promise in relation to *T. roseum* treatment (averaged for fungal inoculation treatment and inoculated substrate).



AVE CUL GRA NIV POA CON

PLATE 6.1. Effect of soil inoculation with different *Fusarium* species, followed by *T. roseum,* on seedling emergence of barley cv. Golden Promise.

With regard to the interaction of the *Fusarium* inoculation with *T. roseum* treatment, it was observed that the inoculation of *T. roseum* 2 weeks before or after *Fusarium* inoculation depressed seedling emergence most markedly with *F. culmorum*, *F. avenaceum* and *F. graminearum* (Figure 6.5). The effects of this fungus with other *Fusarium* species were insignificant. Table 6.2 shows that seed inoculation gave better seedling emergence than soil inoculation.

TABLE 6.2. The effect of seed or soil inoculation with different fungi on the percentage seedling emergence (averaged for *T. roseum* treatment).

INOCULATED SUBSTRATUM	AVE	*FUSARIUM* SPECIES CUL	GRA	NIV	POA	CON
SOIL	61	51	51	81	78	73
SEED	79	59	78	87	83	94

SED(df=126) $\pm$ 5.42

6.3.3 Experiment 3. The effect of seed inoculation of different cereal crop plants with *T. roseum* on seedling emergence

In comparing the pathogenicity of *T. roseum* towards different cereal species and cultivars no differences were observed between hosts when comparing seed germination failures (Appendix XV). However, with regard to incidence of abnormal seedlings, this was increased in all cases by *T. roseum* inoculation **(Plate 6.2,** Table 6.3). The incidence was greatest with the triticale cultivar, Lasko, and least with the oat cultivars.

FIGURE 6.5. Seedling emergence (%) of barley cv. Golden Promise in relation to *Fusarium* species and *T. roseum* treatment (averaged for inoculated substratum).

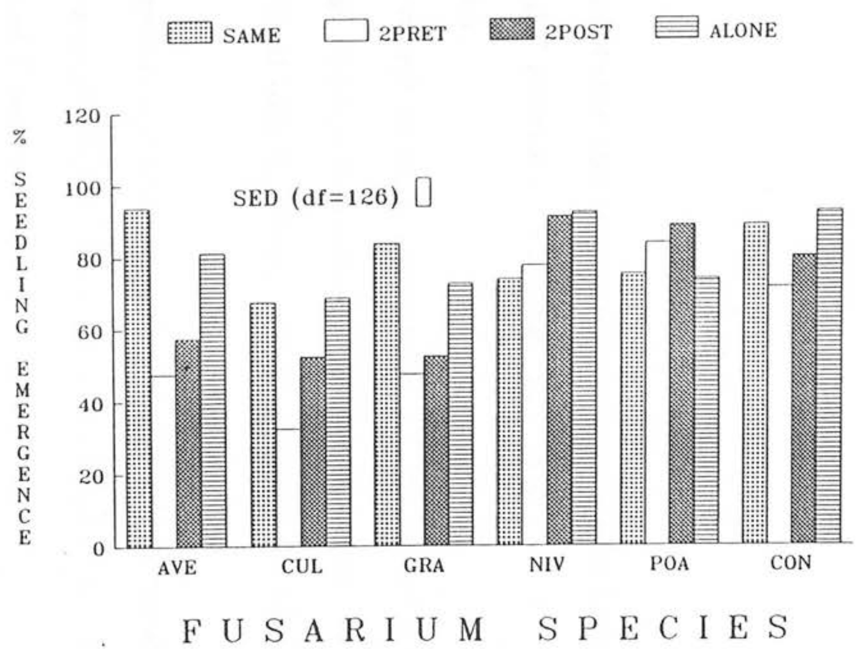


TABLE 6.3. The effect of seed inoculation of *T. roseum* on the percentage of abnormal seedlings of different cereal crop cultivars.

	CULTIVARS						
TREATMENT	1	2	3	4	5	6	7
T. ROSEUM	49	58	81	60	28	17	40
CONTROL	16	9	7	7	7	3	9
SED (df=39) $\pm$ 7.8							

1=AVALON 2=APOSTLE 3=LASKO 4=GERBEL
5=GOLF 6=TRAFALGAR 7=AVALANCHE

Experiment 6.4. The effect of seed inoculation with different inoculum rates of *F. culmorum* and *T. roseum* on the seedling performance of wheat cv. Dollar.

It was found that only when high spore concentrations of *F. culmorum* were used was there a high percentage of ungerminated seeds (Figure 6.6, Plate 6.**3**) the greatest effect being associated with the higher ratio of *F. culmorum* to *T. roseum*.

Figure 6.**7** shows a high percentage of abnormal seedlings with all combinations of spore concentrations except that where there was a low degree of *F. culmorum* with a slightly higher level of *T. roseum*.

FIGURE 6.6. Seed germination failure (%) of wheat cv Dollar in relation to different inoculum mixture rates of *F. culmorum (cu)* and *T. roseum (Tr)* in millions of spores per ml*.

*1=4/20	2=0.0002/20	3=0.002/2	4=0.02/0.2
5=0.2/0.02	6=2/0.002	7=4/0.0002	8=0/0

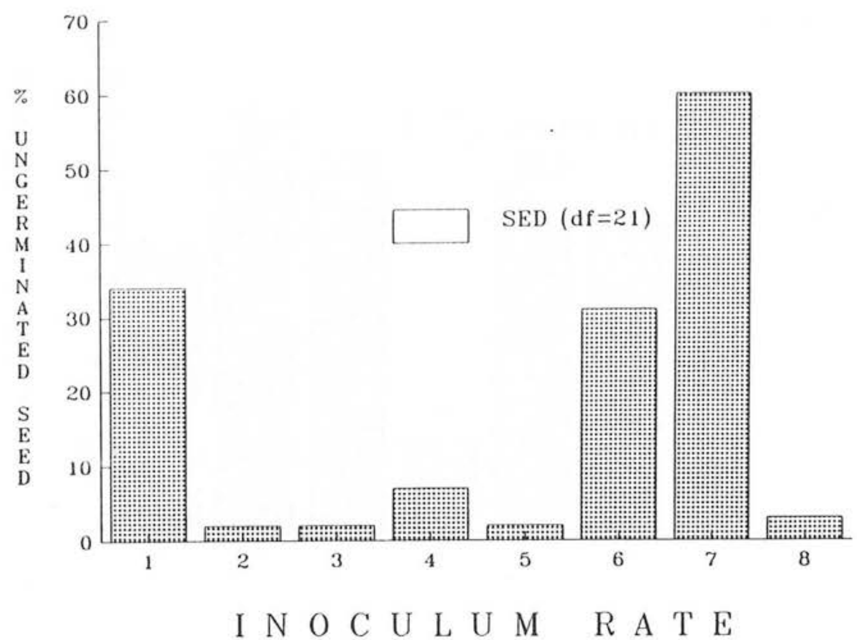
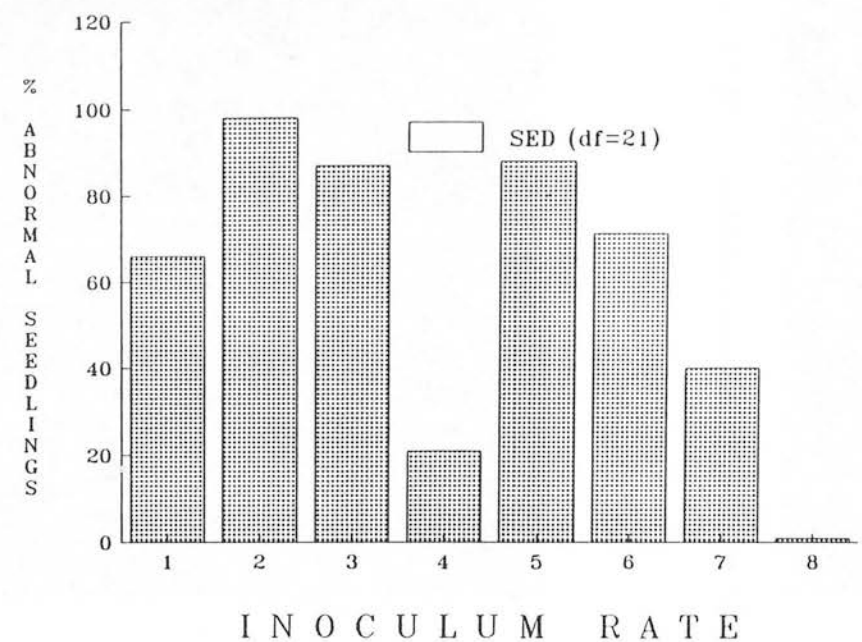


FIGURE 6.7. Abnormal seedlings (%) of wheat cv. Dollar in relation to different inoculum mixture rates of *F. culmorum (cu)* and *T. roseum (Tr)* in millions of spores per ml*.

* 1=4/20	2=0.0002/20	3=0.002/2	4=0.02/0.2
5=0.2/0.02	6=2/0.002	7=4/0.0002	8=0/0



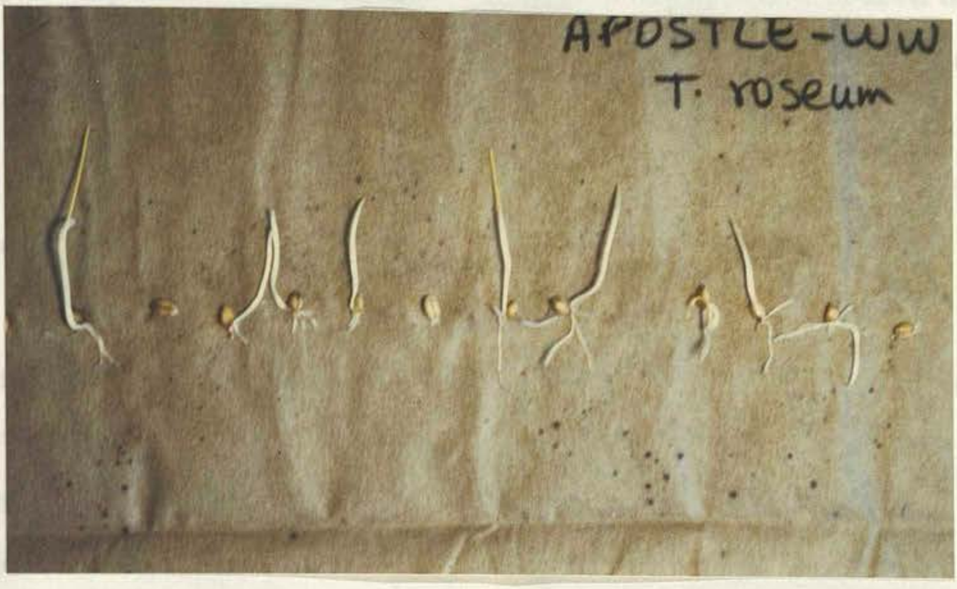


PLATE 6.2. Effect of *T. roseum* seed inoculation on the germination of wheat cv. Apostle.

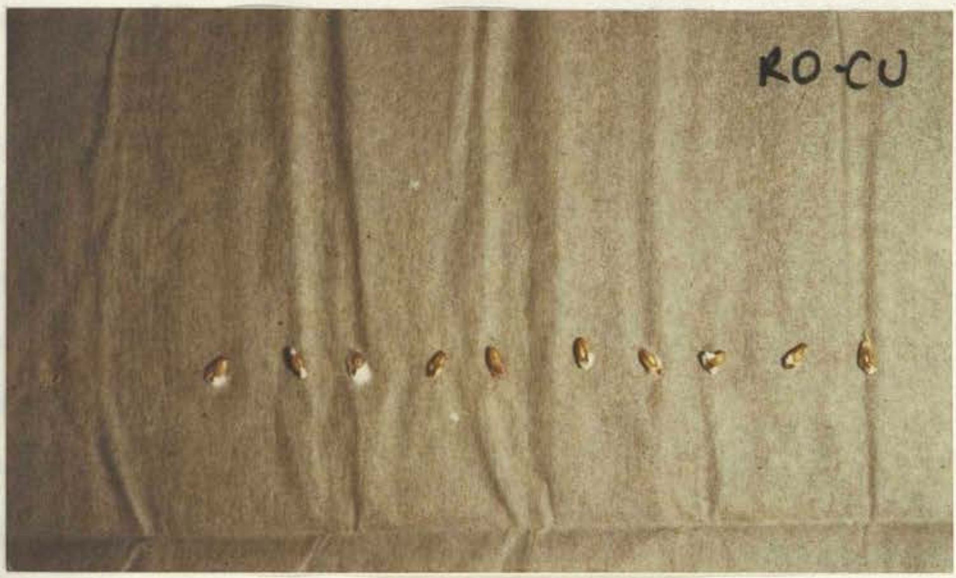


PLATE 6.3. Germination failure of seed inoculated with *T. roseum* (RO) and *F. culmorum* (CU) (wheat cv. Dollar) associated with high spore concentration load of *F. culmorum* (4 million spores per ml).

6.3.5 Experiment 5: Studies of the effect of inoculation of seed of wheat with *Fusarium* species and various fungi on seedling emergence.

In this experiment seed of wheat cv. Dollar, uninfected by pathogens, was inoculated with mixtures of selected fungi plus *Fusarium* species.

Figure 6.8 shows a higher percentage of emergence **failure** when seed was inoculated with *F. culmorum* and *F. avenaceum* followed by *F. graminearum* and to a lesser extent *F. nivale* relative to the controls. On average the combination of *Fusarium* species with the isolate of *Botrytis* spp. gave the highest failure rate followed by *Alternaria* and one isolate of *Penicillium (*PEN1) and *Fusarium* species alone. *Cladosporium* and the other isolate of *Penicillium* (PEN2) combined with the *Fusarium* species tended to give low percentages of germination failure compared with *Fusarium* species alone (Figure 6.9).

From Table 6.4 it may be seen that *Botrytis* alone, and to a slight extent *Alternaria* , adversely affected emergence and both species increased the failure rate associated with *F. avenaceum* and *F. nivale* infection. However both of these *Fusarium* species were not significantly different from the controls. *Cladosporium*, improved the emergence with all *Fusarium* species except *F. nivale* and *Penicillium* (PEN2) had a significant, beneficial effect with *F. culmorum* and *F. poae.*

FIGURE 6.8. Ungerminated seed (%) of wheat cv. Dollar in relation to seed inoculation with different *Fusarium* species (averaged for fungal inoculum treatment).

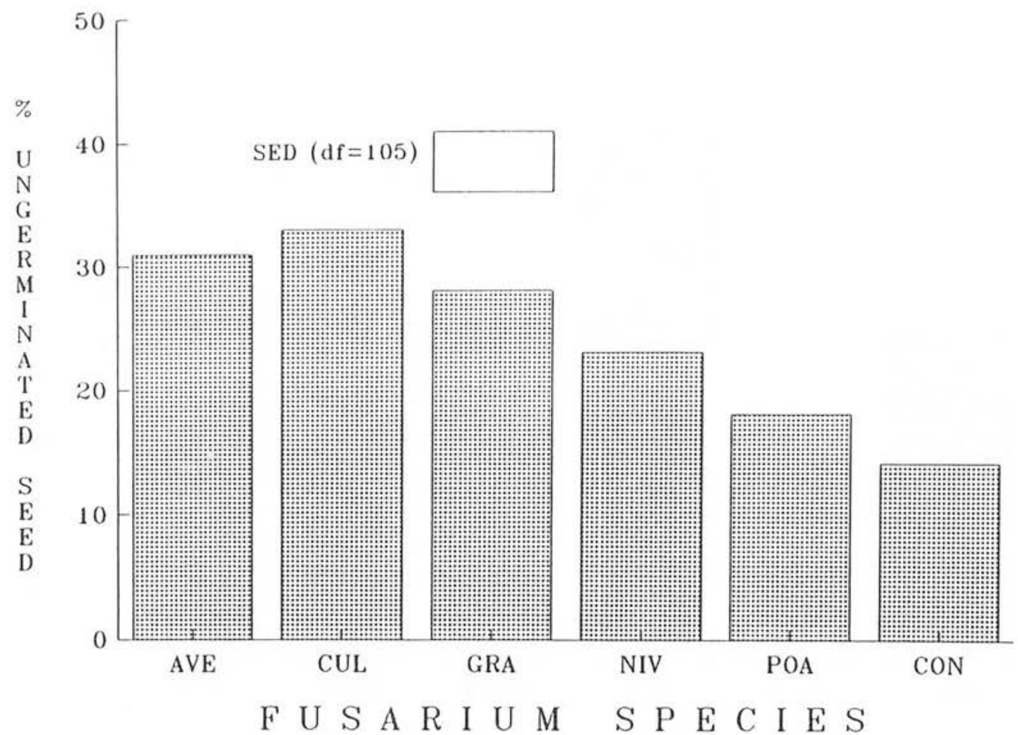


FIGURE 6.9. Ungerminated seed (%) of wheat cv. Dollar in relation to seed inoculation with different fungal inoculum treatments (averaged for species of *Fusarium*).

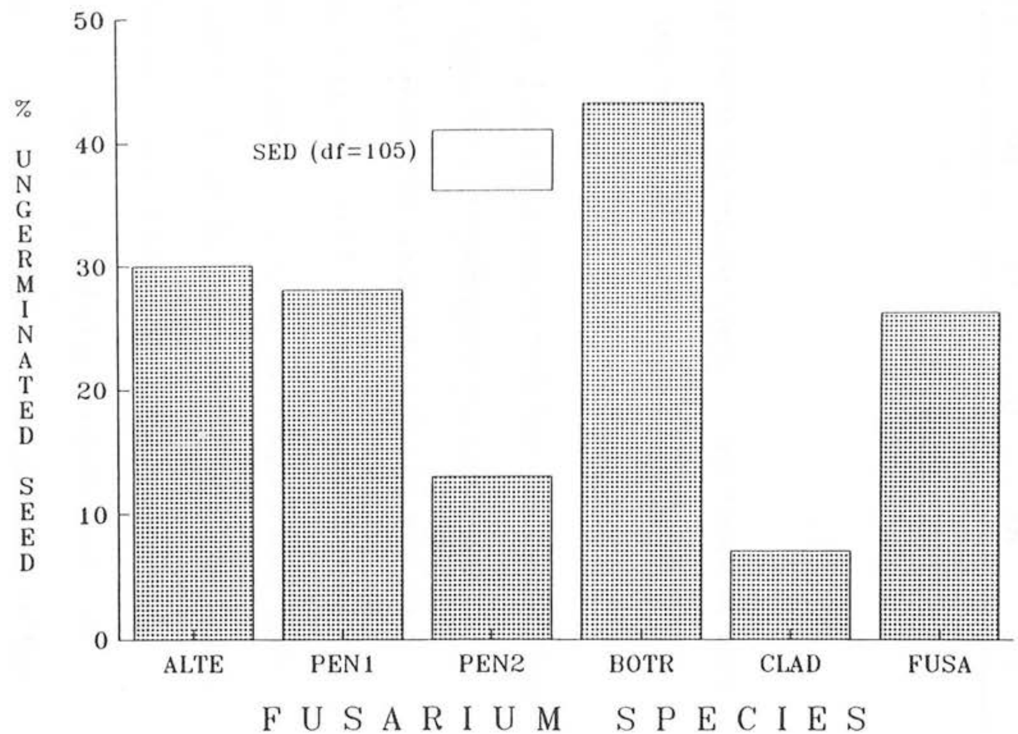


TABLE 6.4. The effect of inoculating wheat seed fungal species on the *Fusarium* species infections. Percentage of ungerminated seed.

	FUSARIUM SPECIES					
FUNGAL SPECIES	AVE	CUL	GRA	NIV	POA	CON
Alternaria	50	30	30	35	18	20
Penicillium (PEN1)	38	53	33	3	35	8
Penicillium (PEN2)	10	25	18	5	8	10
Botrytis	63	35	43	48	33	40
Cladosporium	5	3	10	13	10	3
None	23	50	38	8	38	3

SED (df=105) $\pm$ 12.0

6.4 DISCUSSION

Only a limited number of experiments are reported here on the results of seed and soil inoculations and findings must therefore be regarded as preliminary.

In comparing the effects of artificial seed inoculation with different *Fusarium* on the seedling emergence, once again the most pathogenic proved to be *F. culmorum*, *F. avenaceum* and *F. graminearum* in adversely affecting plant establishment. When seed was inoculated with *T. roseum* in addition to species of *Fusarium* it was observed that the presence of the former fungus varied in its effects in relation to the time that *T. roseum* was inoculated. Overall this fungus tended to aggravate disease but when inoculated in advance with particular *Fusarium* species the percentage of emerged seedlings was increased. The possible reason for this might be that when *T. roseum* is established on or the seed as a saprophyte or weak parasite it competes with and prevents the colonization by the *Fusarium* species. This has been found by Lai and Bruehl

(1968) who also observed a reduced straw colonization by *F. culmorum* when either *C. gramineum* or *Trichoderma* spp. were already colonizing the substratum. Another case of the antagonistic effect of *T. roseum* against *F. graminearum* was recorded by Beratlief & Tircomnicu (1979) who observed that *F. graminearum* was antagonized through the production of some metabolites produced by *T. roseum.* When the fungus was inoculated after the *Fusarium* species, however, the disease tended to be increased. This was observed both with artificially inoculated seed or seed harvested from the ear inoculation, 1987. The possible reason for this could be that when *Fusarium* species are infecting cereal seed, *T. roseum,* as a good competitor and weak parasite, increases the *Fusarium* effect as found by Sing *et al.* (1984) with *F. moniliforme* and *T. roseum* in seed kernels.

A higher percentage of emergence failure was observed when soil was inoculated with the different *Fusarium* species than with seed inoculation, but this was significant only with *F. culmorum, F. avenaceum* and *F. graminearum*. Other workers have found that *F. culmorum* and *F. graminearum* are strong soil-borne competitors (Warren & Kommedahl, 1973) and stronger than *F. nivale* or *F. poae* (Al-Hashimi & Perry, 1986).

SECTION 7

GENERAL DISCUSSION

The results of the experimental studies are specifically discussed in the relevant, previous sections and in this general discussion only some broader aspects of the work and its implications for future research are considered.

F. culmorum was identified as the major *Fusarium* pathogen and this position may be attributed in part to its ability to colonize host tissues extensively and to cause deep-seated infection of seed. However, *F. sambucinum* also showed extensive and internal infection of seed, yet is regarded as only a weak pathogen of cereals. This apparent anomaly may possibly be linked with differences in phytotoxin production, as external metabolites produced by certain *Fusarium* species may account to some degree for their pathogenic effects. It is suggested that further work on the role of phytotoxins in the pathogenicity of the *Fusarium* species infecting cereals would be of scientific interest.

The conflicting evidence on the pathogenic status of *F. nivale* also requires further investigation, with particular reference to the interaction between its parasitic development and temperature. Certainly, it is reported to be a destructive pathogen in the extreme conditions of snow cover, as a cause of snow mould (Wheeler, 1969) and of winter killing in cereals (Zillinsky, 1983).

The results of the present work showed no consistent differences in response of different cereal species or cultivars to *Fusarium* attack, but in the light of other workers findings on cultivar resistance (Parry, *et al.*, 1984; 1986) further studies on sources and the nature of resistance to *Fusarium* infection would be worthwhile.

Fungicide control of *Fusarium* diseases of cereals is essentially based on chemical seed treatments and the development of systemic fungicides have probably improved their effectiveness in providing more practical control. However, the exposure of *Fusarium* species in the field to a wide range of fungicides used to control other pathogens, although conferring some benefit against *Fusarium*, may be creating fungicide insensitivity problems in this group. The assessment of responses of *Fusarium* species to fungicides with different modes of action would be of value in anticipating fungicide insensitivity problems.

Chemical seed treatment may have only a limited effect in controlling soil-borne transmission and it is possible that there is scope for the appraisal of biological control measures against soil-borne *Fusarium* species. There are many reports on the occurrence of *Fusarium*-suppressive soils (Shipton, 1977) and they suggest the potential of antagonistic microorganisms for the control of *Fusarium* pathogens. *T. roseum* was found to inhibit *Fusarium* infection of cereal ears in some circumstances, probably linked to an interference with host factors which are stimulatory to *Fusarium* colonization. However, the effects of this fungus were inconsistent and, moreover, it proved to be pathogenic to cereals. The pathogenic activity of *T. roseum* deserves further investigation. However, preliminary observations **show** *Cladosporium* and an isolate of *Penicillium* reduced disease levels caused by some species of *Fusarium*.

BIBLIOGRAPHY

ABOU-HEILAH, A. N. (1984). Seed-borne fungi of wheat and their control by seed treatments. *Indian Phytopathology*, **37**, 656-659

ADAMS, J. F. (1921). Observations on wheat scab in Pennsylvania and its pathological histology. *Phytopathology* **11**, 115-124.

AL-HASHIMI, M. H. & PERRY, D.A. (1986). Survival and saprophytic ability of *Monographella nivalis* in soil. *Transactions of the British Mycological Society* **86**, 373-379.

ANDERSEN, A. L. (1948). The development of *Gibberella zeae* head blight of wheat. *Phytopathology* **38**, 595-611.

ANDREWS, S. & PITT, J. I. (1986). Selective medium for isolation of *Fusarium* species and dematiaceous Hyphomycetes from cereals. *Applied and Environmental Microbiology* **51**(6), 1235-1238.

ANDRILENAS, P. A. (1974). "Farmers use of pesticides in 1971-Quantities," Agricultural Economic Reprint No. 252. Economic Research Service, U.S. Department of Agriculture, Washington, D. C.

ANDRILENAS, P. A. (1975). "Farmers use of pesticides in 1971-Extent of crop use," Agricultural Economic Reprint No. 268. Economic Research Service, U.S. Department of Agriculture, Washington, D. C.

ANON. (1972). Laboratory techniques- Testing fungi for resistance to fungicides Department of Agriculture, Fisheries and Food. 3 pp..

ANON, (1985). International rules for seed testing- Rules 1985. *Seed Science and Technology* **13**, 299-355.

ANON. (1988). Resistance to fungicides. ADAS P3105, 4 p.

ARX, J. A. von. (1984). Notes on *Monographella* and *Microdichium*. *Transactions of the British Mycological Society* **82**(2), 373-374.

ATANASOFF, D. (1920). *Fusarium* blight (scab) of wheat and other cereals. *Journal of Agricultural Research* **20**, 1-32.

BARNETT, H. L. & HUNTER, B. B. (1972). *Illustrated genera of imperfect fungi.* Minneapolis, Mn: Burgess Publishing Co. 141 p.

BARTLETT, D. H. & BALLARD, H. E. (1975). The effectiveness of guazatine and imazalil as seed treatment fungicides in barley. *Proceedings of the eighth British Insecticide and Fungicide Conference*. 205-211 p.

BARRON, G. L. (1976). *The genera of Hyphomycetes from soil.* New York: Robert E. Krieger Publishing Co. 364 p.

BATEMAN, G. L. (1976) Control of seed-borne *Fusarium nivale* on wheat and barley by organomercury seed treatment. *Annals of Applied Biology* **83**, 245-250.

BATEMAN, G. L. (1977). Effects of organomercury treatment of wheat seed on *Fusarium* seedling disease in inoculated soil. *Annals of Applied Biology* **85**, 195-201

BATEMAN, G. L. (1979). Relationships between *Fusarium nivale* and other microorganisms on seed of wheat and barley. *Transactions of the British Mycological Society* **72**, 245-249.

BATEMAN, G. L. (1983). Response of *Fusarium nivale* in wheat and barley caryopses to organomercury treatment in relation to site of infection and microbial antagonism. *Transactions of the British Mycological Society* **81**, 141-183.

BENNETT, F. T. (1928). On two species of *Fusarium*, *F. culmorum* (W.G.Sm.) Sacc. and *F. avenaceum* (Fr.) Sacc., as parasites of cereals. *Annals of Applied Biology* **17**, 43-58.

BENNETT, F. T. (1933). *Fusarium* species on British cereals. *Fusarium nivale* (Fr.) Ces. (=*Calonectria graminicola* (Berk. & Br.) Wr.). *Annals of Applied Biology* **20**, 272-290.

BERATLIEF, Z. & TIRCOMNICU, M. (1979). *In vitro* studies on the mode of action of some fungi from wheat seeds antagonistic to *Fusarium graminearum* (Schw.). *Annale Institutulvi de Cercezari Pentru Protectia Plantelor* **14**, 39-49 (Abstr.)

BILAI, V. I. (1952). Taxonomy of the Sporotrichiella section of the genus *Fusarium*. *Depov Akademiya Ukrainskoi. SSR.* **5**, 415-419.

BILAI, V. I. (1955). *The Fusaria (Biology and Systematics)*. Kiev: Akademiya Naukova, 320 pp.

BILAI, V. I. (1970a). Experimental morphogenesis in the fungi of the genus *Fusarium* and their taxonomy. *Annales Academiae Scientiarum Fennicae (Biologica)* **4**, 7-18.

BILAI, V. I. (1970b). Phytopathological and hygienic significance of representatives of the section Sporotrichiella in the genus *Fusarium* Lk. *Annales Academiae Scientiarum Fennicae (Biologica)* **4**, 19-27.

BILAI, V. I. (1977). *Fusaria*. Kiev: Naukova Dumka.

BILAI, V. I. (1978a). Principles of the taxonomy and pathogenic structure of species of the genus *Fusarium* Lk. ex Fr. *Mikrobiolohichniyi Zhurnal* **40**, 148-156.

BILAI, V. I. (1978b). Mycological aspects of alimentary toxicoses. *Mykrobiolohichniyi Zhurnal* **40**, 205-213.

BOOTH, C. (1971). *The genus* *<u>Fusarium</u>*. Kew, Surrey: Commonwealth Mycological Institute. 237 pp.

BOOTH, C. (1975). The present status of *Fusarium* taxonomy. *Annual Review of Phytopathology* **13**, 83-93.

BOOTH, C. (1977). *Fusarium laboratory guide to the identification of major species.*Kew, Surrey: Commonwealth Mycological Institute, 58 pp.

BOOTH, C. (1981). Perfect states (teleomorphs) of *Fusarium* species. In, *"Fusarium: diseases, biology and taxonomy"* (ed. P. E. Nelson, T. A. Toussoun & R. J. Cook), pp. 445-452. University Park and London: Pennsylvania State University Press, 457 pp.

BROWN, E. (1928). The interpretation of germination tests. *Proceedings of the International Seed Testing Association* **2**, 66-72.

BURGESS, L. W., DODMAN, R. L., PONT, W. & MAYERS, P. (1981). *Fusarium* diseases of wheat, maize and grain sorghum in Eastern Australia. In, *"Fusarium: disease, biology and taxonomy"* (ed. P. E. Nelson, T. A. Toussoun & R. J. Cook), pp. 64-76. University Park and London: Pennsylvania State University Press.

BURGESS, L. W., NELSON, P. E. & TOUSSOUN, T. A. (1982). Characterization, geographic distribution, and ecology of *Fusarium crookwellense* sp. nov. *Transactions of the British Mycological Society* **79**, 497-505.

BURGESS, L. W., WEARING, A. H. & TOUSSOUN, T. A. (1975). Survey of *Fusaria* associated with crown rot of wheat in Eastern Australia. *Australian Journal of Agricultural Research* **26**, 791-799.

BUTLER, F. C. (1959). Saprophytic behaviour of some cereal root-rot fungi. I. Saprophytic colonization of wheat straw. *Annals of Applied Biology* **40**, 234-291.

BUTLER, F. C. (1961). Root and foot rot diseases of wheat. *New South Wales Department of Agricultural Science, Bulletin* 77, 98 pp.

CASANOVA, A., DOHLER, R., FARRANT, D. M. & RATHMELL, W. G. (1977). The activity of the fungicide Nuarimol against diseases of barley and other cereals. *Proceedings 1977 British Crop Protection Conference- Pests and Diseases*. 1-7 p.

CASSINI, R. (1981). *Fusarium* diseases of cereals in western Europe. In, *"Fusarium: disease, biology and taxonomy"* (ed. P. E. Nelson, T. A. Toussoun & R. J. Cook). pp. 55-64. University Park and London: Pennsylvania State University Press.

CHAND, T. & LOGAN, C. (1984). Antagonists and parasites of *Rhizoctonia solani* and their efficacy in reducing stem canker of potato under controlled conditions. *Transactions of the British Mycological Society* **83**, 107-109.

CHASTAGNER, G. A. & VASSEY, W. E. (1982). Occurrence of Iprodione-tolerant *Fusarium nivale* under field conditions. *Plant Disease* 66, 112-114.

CHRISTENSEN, C. M. & KAUFMAN, H. (1969). *Grain storage.* Minnesota: University of Minnesota Press. 154 pp.

CLARK, M. R. M. (1977). The incidence and fungicidal control of some stem base and root pathogens of barley in west Scotland. *Proceedings of a Symposium on Problems of Pests and Diseases Control in Northern Britain, Dundee, 1977*, 16-19.

CLARK, M. R. M. (1981). The effects of organomercury seed treatment on barley artificially inoculated with *Fusarium* spp. *EPPO Bulletin* **11**, 317-322.

COLHOUN, J. (1970). Epidemiology of seed-borne *Fusarium* diseases of cereals. *Annales Academiae Scientiarum Fennicae (Biologica)* **4**, 31-36.

COLHOUN, J. (1973). Effects of environmental factors on plant disease. *Annual Review of Phytopathology* **11**, 343-364.

COOK, R. J. (1967). *Gibberella avenacea* sp. nov., perfect stage of *Fusarium roseum* f. sp. *cerealis* "Avenaceum." *Phytopathology* **57**, 732-736.

COOK, R. J. (1968). *Fusarium* root and foot rot in cereals in the Pacific Northwest. *Phytopathology* **58(1)**, 127-131.

COOK, R. J. (1981a). *Fusarium* diseases in the People's Republic of China. In, "*Fusarium: disease, biology and taxonomy*" (ed. P. E. Nelson, T. A. Toussoun & R. J. Nelson), pp. 53-55. University Park and London: Pennsylvania State University Press.

COOK, R. J. (1981b). *Fusarium* diseases of wheat and other small grains in North America. In, "*Fusarium: disease, biology and taxonomy*" (ed. P. E. Nelson, T. A. Toussoun & R. J. Nelson), pp. 39-52. University Park and London: Pennsylvania State University Press.

DE TEMPE, J. (1958). Three years of field experiments on seed-borne fungi and seed treatments of cereals. *Proceedings of the International Seed Testing Association* **23**, 38-67.

DEKKER, J. (1973). Selectivity of and resistance against systemic fungicides. *OEPP/EPPO Bulletin* **10**, 47-57.

DELP, C. J. (1980). Coping with resistance to plant disease control agents. *Plant Disease* **64**, 652-657.

DICKINSON, C. H. & SKIDMORE, A. M. (1976). Interactions between germinating spores of *Septoria nodorum* and philloplane fungi. *Transactions of the British Mycological Society* **66**, 45-56.

DICKINSON, C. H. & WALLACE, B. (1976). Effects of late applications of foliar fungicides on activity of micro-organisms in winter wheat flag leaves. *Transactions of the British Mycological Society* **67**, 103-112.

DICKSON, J. G. (1947). *Diseases of field crops*. New York: McGraw Hill Book Co. Inc. 429 pp.

DUBEN, J. & FEHRMANN, H. (1979). Occurrence and pathogenicity of *Fusarium* species on winter wheat in West Germany. II. Comparison of pathogenicity on seedlings, haulm bases, and ears. *Zeitschrift fur pflanzenkrankheiten und Pflanzenschutz* 86, 705-728.

ELLIS, M. B. (1971). *Dematiaceous Hyphomycetes.* Kew, Surrey: Commonwealth Mycological Institute, 608 pp.

ELLIS, M. B. (1976). *More dematiaceous Hyphomycetes.* Kew, Surrey: Commonwealth Mycological Institute, 507 pp.

EVANS, E. (1971). Problems and progress in the use of systemic fungicides. *Proceedings of the 6th British Insecticide and Fungicide Conference.* 758-763.

FENSTER, C. R., BOOSALIS, M. G. & WEIHING, J. L. (1972). Date of planting studies of winter wheat and winter barley in relation to root and crown rot grain yields and quality. *University of Nebraska-Lincoln College. The Agricultural Experimental Station, Research Bulletin* **250**, 32 pp.

FEHRMANN, H. (1985). Resistance to benzimidazoles in *Pseudocercosporella herpotrichoides. EPPO Bulletin* **15**, 477-483.

FEHRMANN, H. (1988a). *Fusarium culmorum.* In, *"European Handbook of plant diseases"* (ed. I. M. Smith, J. Dunez, D. H. Phillips, R. A. Lelliott & S. A. Archer). 287-289. Oxford, London, Edinburgh: Blackwell Scientific Publications.

FEHRMANN, H. (1988b). *Monographella nivalis.* In, *"European Handbook of plant diseases"* (ed. I. M. Smith, J. Dunez, D. H. Phillips, R. A. Lelliott & S. A. Archer). 335-337. Oxford, London, Edinburgh: Blackwell Scientific Publications.

FISHER, N. L., BURGESS, L. W. TOUSSOUN, T. A. & NELSON, P. E. (1982). Carnation leaves as a substrate and for preserving cultures of *Fusarium* species. *Phytopathology* 72:151-153.

FOISTER, C. E. (1961). The economic plant diseases of Scotland. *Department of Agriculture, Food and Fisheries of Scotland. Technical Bulletin* **1**, 27-34.

FORBES, R. S. & DICKINSON, C. H. (1977). Behaviour of *Fusarium avenaceum* in soil growth analysis plates. *Transactions of the British Mycological Society* **69**, 197-205.

FORRER, H. R., RIJSDIJK, F, H. & Zadoks, J, C. (1982). Can mildew assist in the entry of *Fusarium* fungi into wheat leaves? *Netherlands Journal of Plant Pathology* **88**, 123-125.

FRANCIS, R. G. & BURGESS, L. W. (1977). Characteristics of two populations of *Fusarium roseum* 'Graminearum' in Eastern Australia. *Transactions of the British Mycological Society* **68**, 421-427.

FREEMAN, G. G. (1955). Biological properties of trichothecin, an antifungal substance from *Trichothecium roseum. Journal of General Microbiology* **12**, 213-221.

FREEMAN, G. G. & MORRISON, R. I. (1949). The isolation and chemical properties of trichothecin, an antifungal substance from *Trichothecium roseum*. *Nature* (London), **162**, 30.

FRITZ, T. (1966). Influence of temperature and parasitic fungi on germination capacity of cereal seed. *Proceedings of the International Seed Testing Association* **31**, 711-717.

FROTO, U. B. & BAILEY DE IBARRA, A. (1983). Mecanismos de action de algunos organismos antagonistas probados contra quince fitopatogenos. *Revista Mexicana de Fitopatologia* **2**, 35-39.

GAMS, W. & MULLER, E. (1980). Conidiogenesis of *Fusarium nivale* and *Rhynchosporium oryzae* and its taxonomic implications. *Netherlands Journal of Plant Pathology* **86(1)**, 45-53.

GARRETT, S. D. (1970). Biology of root-infecting fungi. Cambridge: Cambridge University Press. 293 pp.

GAÜMANN, E. (1957). Fusaric acid as a wilt toxin. *Phytopathology* **47**, 342-357.

GAÜMANN, E. (1958) The mechanism of fusaric acid injury. *Phytopathology* **48**, 670-685.

GEORGOPOULOS, S. G. (1969). The problem of fungicide resistance. *BioScience* **19**, 971-973.

GEORGOPOULOS, S. G. & SKILAKAKIS, G. (1986). Genetic variability in the fungi and the problem of fungicide resistance. *Crop Protection* **5**, 299-305.

GEORGOPOULOS, S. G. & ZARACOVITIS, C. (1967). Tolerance of fungi to organic fungicides. *Annual Review of Phytopathology* **5**, 109-130.

GERLACH, W. (1970). Suggestions to an acceptable modern *Fusarium* system. *Annales Academiae Scientiarum Fenicae (Biologica)* **4**, 37-49.

GERLACH, W. (1981). The present concept of *Fusarium* classification. In, "*Fusarium: disease, biology and taxonomy*" (ed. P. E. Nelson, T. A. Toussoun & R. J. Cook), pp. 413-426. University Park and London: Pennsylvania State University Press, 457 pp.

GERLACH, W. & NIRENBERG, H. (1982). *The genus Fusarium - A pictorial Atlas*. Mitt. Biol. Bundesanst. Land-Forstwirtsch. Berlin-Dahlem 406 pp.

GIANNOPOLITIS, C. N. (1978). Occurrence of strains of *Cercospora beticola* resistant to triphenyltin fungicides in Greece. *Plant Disease Reporter* 62, 205-208.

GIRISHAM, S., REDDY, S. M. & REDDY, V. K. (1985). Effect of culture filtrates of some seed-borne fungi of pearl millet on its seed germination, root and shoot elongation. *National Academy Science Letters* **8**, 193-195.

GORDON, W. L. (1935). Species of *Fusarium* isolated from field crops in Manitoba. *Proceedings of the World's Grain Exhibition Conference* 2, 298-299.

GORDON, W. L. (1939). *Fusarium* species associated with diseased cereals in Manitoba. *Phytopathologia* 29, 7 (Abstr.).

GORDON, W. L. (1944). The occurrence of *Fusarium* species in Canada. I. Species of *Fusarium* isolated from farm samples of cereal seed in Manitoba. *Canadian Journal of Research* 22, 282-286.

GORDON, W. L. (1952). The occurrence of *Fusarium* species in Canada. II. Prevalence and taxonomy of *Fusarium* species in cereal seed. *Canadian* Journal of Botany 30, 209-251.

GORDON, W. L. (1954a). The occurrence of *Fusarium* species in Canada. III. Taxonomy of *Fusarium* species in the seed of vegetables, forage, and miscellaneous crops. *Canadian Journal of Botany* 32, 576-590.

GORDON, W. L. (1954b). The occurrence of *Fusarium* species in Canada. IV. Taxonomy and prevalence of *Fusarium* species in the soil of cereal plots. *Canadian Journal of Botany* 32, 622-629.

GORDON, W. L. (1956a). The occurrence of *Fusarium* species in Canada. V. Taxonomy and geographic distribution of *Fusarium* species in soil. *Canadian Journal of Botany* 34, 833-846.

GORDON, W. L. (1956b). The taxonomy and habitats of the *Fusarium* in Trinidad, B. W. I. *Canadian Journal of Botany* 34, 847-864.

GORDON, W. L. (1959). The occurrence of *Fusarium* species in Canada. VI. Taxonomy and geographic distribution of *Fusarium* species in plants, insects, and fungi. *Canadian Journal of Botany* 37, 257-290.

GORDON, W. L. (1960a). The taxonomy and habitats of *Fusarium* species from tropical and temperate regions. *Canadian Journal of Botany* 38, 643-658.

GORDON, W. L. (1960b). Distribution and prevalence of *Fusarium moniliforme* Sheld. (*Gibberella fujikuroi* (Saw.) Wr.) producing substances with gibberellin-like biological properties. *Nature*, London 186, 698-700.

GORDON, W. L. (1960c). Is *Nectria haematococca* Berk. & Br. the perfect stage of *Fusarium oxysporum* Schl. forma *pisi* (Lindf.) Snyder & Hansen? *Nature*, London 186, 903.

GORDON, W. L. (1961). Sex and mating types in relation to the production of perithecia by certain species of *Fusarium*. *Proceedings of the Canadian Phytopathological Society* 28, 11.

GORDON, W. L. (1965). Pathogenic strains of *Fusarium oxysporum*. *Canadian Journal of Botany* 43, 1309-1318.

HENDRIX, F. F. & CAMPBELL, W. A. (1973). *Pythium* as plant pathogens. *Annual Review of Phytopathology* 11, 77-98.

HEWETT, P. D. (1983). Seed-borne *Gerlachia nivalis (Fusarium nivale)* and reduced establishment of winter wheat. *Transactions of the British Mycological Institute* **80**, 185-186.

HEYDECKER, W. (1969). The vigour of seeds- A review. *Proceedings of the International Seed Testing Association* **34**, 201-219.

HEYDECKER, W. (1972). Vigour. In, *"Viability of seeds"* (ed. E. H. Roberts). 209-252 p. London: Chapman and Hall.

HILL, J. P., FERNANDEZ, J. A. & McSHANE, M. S. (1983). Fungi associated with common root rot of winter wheat in Colorado and Wyoming. *Plant Disease* **67**, 795-797.

IRETA, M. J. (1986). Estimatión de pérdidas en trigo (*Triticum* sp. L.) causadas por la roña (*Fusarium graminearum* Schw.). Tésis de Maestro en Ciencias. Colegio de Postgraduados, Montecillos, México 86 pp.

ISHII, K., KOBAYASHI, J., UENO, Y. & ICCHINOE, M. (1986). Occurrence of trichothecin in wheat. *Applied and Environmental Microbiology* **55**, 331-333. (Abstr.).

JEFFRIES, J. C. (1978). Transmission studies on the potato pathogens *Fusarium solani* var. *coeruleum* and *F. sulphureum*. PhD Thesis. University of Edinburgh, Scotland 195 pp.

JENKINS, J. E. E., CLARK, W. S. & BUCKLE, A. E. (1988). *Fusarium* diseases of cereals. *Home-Grown Cereals Authority Research Review No. 4.* 89 pp.

JENKINS, J. E. E., CLARK, W. S. & BUCKLE, A. E. (1989). Review of *Fusarium* diseases of cereals. *The Agronomist* **3**, 16-17.

JENKYN, J. F. & PLUMB, R. T. (1982). Strategies for the control of cereal diseases. Oxford: Blackwell Scientific Publications 219 pp.

JOFFE, A. Z. (1974). A modern system of *Fusarium* taxonomy. *Mycopathologia et Mycologia Applicata* **53**, 201-228.

JOFFE, A. Z. (1986). *Fusarium species: their biology and toxicology.* New York: John Wiley & Sons. 588 pp.

JONES, D. C. & CLIFFORD, B. C. (1983). *Cereal diseases: their pathology and control.* Suffolk: BASF United Kingdom Ltd., 309 pp.

JONES, D. R., SLADE, M. D. & BIRKS, K. A. (1989). Resistance to organomercury in *Pyrenophora graminea. Plant Pathology* **38**, 509-513.

JOSEPOVITS, G. & DOBROVOLSZKY, A. (1985). A novel mathematical approach to the prevention of fungicide resistance. *Pesticide Science* **16**, 17-22.

KABLE, P. F. & JEFFERY, H. (1980). Selection for tolerance in organisms exposed to sprays of biocide mixtures: a theoretical model. *Phytopathology* **70**, 8-12.

KELMAN, A. & COOK, R. J. (1977). Plant pathology in the People's Republic of China. *Annual Review of Phytopathology* **17**, 409-429.

KOMADA, H. (1975). Development of a selective medium for quantitative isolation of *Fusarium oxysporum* from natural soil. *Review of Plant Protection Research* **8**, 114-125.

KUMAR, V. & SHETTY, H. S. (1985). An ear kernel rot of maize by *Trichothecium roseum*. *Current Science*, India **54**, 486-487. (Abstr.).

LAI, P. & BRUEHL, G. W. (1968). Antagonism among *Cephalosporium gramineum, Trichoderma* spp., and *Fusarium culmorum*. *Phytopathology* **58**, 562-566.

LEVY, Y., LEVY, R. S. & COHEN, Y. (1983). Buildup of a pathogen subpopulation resistance to a systemic fungicide under various control strategies: A flexible simulation model. *Phytopathology* **73**, 1475-1480.

LEVY, Y. & LEVY, R. S. (1986). Control strategies using systemic fungicides for limiting disease development and resistance buildup: Practical implications of a simulation model. *Phytoparasitica* **14**, 303-312.

LIN, Y. S. & COOK, R. J. (1979). Suppression of *Fusarium roseum* 'Avenaceum' by soil microorganisms. *Phytopathology* **69**, 384-388.

LINDSEY, D. (1965). Ecology of plant pathogens in soil. III. Competition between soil fungi. *Phytopathology* **55**, 104-110.

LITSCHKO, L. & BURPEE, L. L. (1987). Variation among isolates of *Microdichium nivale* collected from wheat and turfgrasses. *Transactions of the British Mycological Society* **89**(2), 232-256.

LOCKE, T., MOON, L. M. & EVANS, J. (1987). Survey of benomyl resistance in *Fusarium* species on winter wheat in England and Wales in 1986. *Plant Pathology* **36**, 589-593.

LOGAN, C., LITTLE, W. G. & COOKE, L. R. (1984). Preliminary experiments with biological control of diseases of potato caused by *Rhizoctonia solani* in Northern Ireland. *Proceedings Crop Protection in Northern Britain*. 120-125 p.

LUHANGA, J. H. (1979). The effects of seed-borne fungi on seed vigour in cereals. M. Sc. Thesis. University of Edinburgh, 78 pp.

MALALASEKERA, R. A. & COLHOUN, J. (1969). *Fusarium* diseases of cereals. V. A technique for the examination of wheat seed infected with *Fusarium culmorum*. *Transactions of the British Mycological Society* **52**, 187-193.

MALALASEKERA, R. A. SANDERSON, F. R. & COLHOUN, J. (1973). *Fusarium* diseases of cereals. IX. Penetration and invasion of wheat seedlings by

Fusarium culmorum and *F. nivale*. *Transactions of the British Mycological Society* **60(3)**, 453-462.

MALAN, G. E. (1969). Azione disgregatrice del *Fusarium nivale* sulle di segale in natura. *Nuovo Giornale Botanico Italiano N. S.* **56**, 244-246.

MALON, J. P. & LORIMER, R. (1975). The incidence of pathogenic fungi in Northern Ireland barley and oat seed samples. *Plant Pathology* **24**, 140-143.

MARTIN, J. P. (1950). Use of acid, rose bengal, and streptomycin in the plate method for estimating soil fungi. *Soil Science* **69**, 215-232.

MARTIN, R. A. & JOHNSTON, H. W. (1982). Effects and control of *Fusarium* diseases of cereal grains in the Atlantic Provinces. *Canadian Journal of Plant Pathology 4*, 210-216.

MATHIS, A., FORRER, H. R. & HESSLER, C. (1986). Powdery mildew pustules supporting *Fusarium culmorum* infection of wheat leaves. *Plant Disease* **70(1)**, 53-54.

McKAY, R. (1957). Ear blight, cereal scab, seedling blight of wheat and root rots of oats. In, *"Cereal Diseases in Ireland"* 74-83 p. Dublin: Arthur Guiness.

McMULLEN, M. P. & STACK, R. W. (1983). Effects of isolation techniques and media on the differential isolation of *Fusarium* species. *Phytopathology* **73(3)**, 458-462.

MESSIAEN, C. M. & CASSINI, R. (1968). Recherches sur les fusarioses. IV. La systematique des *Fusarium*. *Annals Epiphyties* **19**, 387-454.

MESSIAEN, C. M. & CASSINI, R. (1981). Taxonomy of *Fusarium*. In, "*Fusarium: disease, biology and taxonomy*" (ed. P. E. Nelson, T. A. Toussoun & R. J. Cook), pp. 427-445. University Park and London: Pennsylvania State University Press, 457 pp.

MESTERHAZY, A. (1974). *Fusarium* diseases of wheat and triticale in South-east Hungary. *Cereal Research Communications* **2**, 167-173.

MESTERHAZY, A. & ROWAISHED, A. K. (1977). Analysis of symptoms caused by *Fusarium graminearum* Schwabe and its relation to powdery mildew of wheat. *Acta Phytopathologica Academiae Scientiarum Hungaricae* **12**, 289-301.

MILLAR, C. S. & COLHOUN, J. (1969a). *Fusarium* diseases of cereals. IV. Observations on *Fusarium nivale* on wheat. *Transactions of the British Mycological Society* **52(1)**, 57-66.

MILLAR, C. S. & COLHOUN, J. (1969b). *Fusarium* diseases of cereals. VI. Epidemiology of *Fusarium nivale* on wheat. *Transactions of the British Mycological Society* **52(2)**, 195-204.

MILGROOM, M. G. & FRY, W. E. (1988). A simulation analysis of the epidemiological principles for fungicide resistance management in pathogen populations. *Phytopathology* 78, 565-570.

MILGROOM, M. G., LEVIN, S. A. & FRY, W. E. (1989). Population genetics theory and Fungicide resistance. In, *"Plant disease epidemiology"* Vol. 2 Genetics, resistance and management (ed. K. R. Leonard & W. E Fry), pp. 340-367. New York: McGraw-Hill Publishing Company.

NAIK, D. M. & BUSCH, L. V. (1978). Stimulation of *Fusarium graminearum* by maize pollen. *Canadian Journal of Botany* **56**, 1113-1117.

NASH, S. M. & SNYDER, W. C. (1962). Quantitative estimations by plate counts of propagules of the bean root rot *Fusarium* in field soils. *Phytopathology* **52**, 567-572.

NEERGAARD, P. (1977). *Seed Pathology*. Volume I. London: The MacMillan Press Ltd. 839 pp.

NELSON, P. E., TOUSSOUN, T. A. & MARASAS, W. F. (1983). *Fusarium species: an illustrated manual for identification*. University Park and London: Pennsylvania State University Press, 193 pp.

NICHOLSON, J. F., MEYER, W. A., SINCLAIR, J. B. & BUTLER, J. D. (1971). Turf isolates of *Sclerotinia homeocarpa* tolerant to Dyrene. *Phytopathologische. Zeitschrift* **72**, 169-173.

NIRENBERG, H. I. (1981). A simplified method for identifying *Fusarium* spp. occurring on wheat. *Canadian Journal of Botany* **59**, 1599-1609.

NOBLE, M. (1970). Seed-borne infection in Scottish cereals. *Annales Academiae Scientiarum Fennicae* **168**, 61-62.

NOBLE, M. (1971). Seed pathology. In, *"Diseases of crop plants"* (ed. J. H. Western), 21-36. London: The MacMillan Press Ltd.

NOBLE, M. & MONTGOMERIE, I. G. (1955). Seed-borne oat diseases. Straw-breaking and brown foot-rot. *Scottish Agriculture* **34**, 51-52.

NOBLE, M., MacGARVIE, Q. D., HAMS, A. F. & LEAFE, E. L. (1966). Resistance to mercury of *Pyrenophora avenae* in Scottish seed oats. *Plant Pathology* **15**, 23-28.

OGAWA, J. M., GILPATRICK, J. D. & CHIARAPPA, L. (1977). Review of plant pathogens resistance to fungicides and bactericides. *FAO Plant Protection Bulletin* **25**, 97-111.

OSWALD, J. W. (1949). Cultural variation, taxonomy and pathogenicity of *Fusarium* species associated with cereal root rots. *Phytopathology* **39** 359-376.

OSWALD, J. W. (1950). Etiology of cereal root and foot rots in California. *Hilgardia* **19(15)**, 447-462.

PAPAVIZAS, G. C. (1967). Evaluation of various media and antimicrobial agents for isolation of *Fusarium* from soil. *Phytopathology* **57**, 848-852.

PAPENDICK, R. I. & COOK, R. J. (1974). Plant water stress and development of *Fusarium* foot rot in wheat subjected to different cultural practices. *Phytopathology* 64, 358-363.

PARMETER, J. R. & HOOD, J. R. (1961). The use of *Fusarium* culture filtrate media in the isolation of fusaria from soil. *Phytopathology* **51**, 164-168.

PARRY, D. W., BAYLES, R. A. & PRIESTLEY, R. H. (1984). Resistance of winter wheat varieties to ear blight (*Fusarium culmorum*). *Journal of the National Institute of Agricultural Botany* **16**, 465-468.

PARRY, D. W., BAYLES, R. A. & PRIESTLEY, R. H. (1986). Resistance of winter wheat varieties to ear blight caused by *Fusarium avenaceum* and *F. culmorum*. *Annals of Applied Biology* **106**, 164-165.

PENNYPACKER, B. W. (1981). Anatomical changes involved in the pathogenesis of plants by *Fusarium*. In, "*Fusarium: disease, biology and taxonomy*" (ed. P. E. Nelson, T. A. Toussoun & R. J. Cook), pp. 401-408. University Park and London: Pennsylvania State University Press, 457 pp.

PERRY, D. A. (1967). Seed vigour and field establishment in peas. *Proceedings of the International Seed Testing Association* **32**, 3-12.

PERRY, D. A. (1969). Seed vigour in peas (*Pisum sativum*). *Proceedings of the International Seed Testing Association* **34**, 221-232.

PERRY, D. A. (1977). A vigour test for seeds of barley (*Hordeum vulgare*) based on measuring of plumule growth. *Seed Science and Technology* **5**, 709-719.

PERRY, D. A. (1986). Pathogenicity of *Monographella nivalis* to spring barley. *Transactions of the British Mycological Society* **86**, 287-293.

PLATENKAMP, R. G. H. & BOLLEN, G. L. (1973). The effect of benomyl sprays on the root mycoflora of rye. *Acta Botanica Neerlandica* **22**, 168.

PONCHET, J. (1966). Etudes communautes mycopericarpiques du caryopse de ble. *Annales des Epiphyties* **17**, 1-111.

PUGH, G., JOHANN, W. H. & DICKSON, J. G. (1933). Factors affecting infection of wheat heads by *Gibberella saubinetii*. *Journal of Agricultural Research* **46**, 771-797.

RAILLO, A. (1935). Diagnostic estimation of morphological and cultural characters in the genus *Fusarium*. *Phytopathology* **7**, 1-100.

RAILLO, A. (1936). Systematics and methods for the determination of the species of the genus *Fusarium*. *Acta Botanica Institute Academiae Scientiarum USSR* **2-3**, 803-857.

RAILLO, A. (1949). *Griby iz roda Fusarium*. Moscow: 419 pp. Government Publishers of Agricultural Literature.

RAILLO, A. (1950). *Fungi of the genus Fusarium*. Moscow: 415 pp Government Publishers of Agricultural Literature.

RENNIE, W. J. & RICHARDSON, M. J. (1983). Seed-borne pathogens and the production of quality cereal seed in Scotland. *Seed Science and Technology* **11**, 1115-1127.

SAMUELS, J. B. & HALLETT, I. C. (1983). *Microdochium stoveri* and *Monographella stoveri*, new combinations for *Fusarium stoveri* and *Micronectriella stoveri*. *Transactions of the British Mycological Society* **81**, 473-483.

SCHROEDER, H. W. & CHRISTENSEN, J. J. (1963). Factors affecting resistance of wheat to scab caused by *Gibberella zeae*. *Phytopathology* **53**, 831-838.

SHIPTON, P. J. (1977). Monoculture and soil-borne plant pathogens. *Annual Review of Phytopathology* **15**, 387-407.

SING, K., SING, T. & SING, D. (1985). Colonization of corn seeds by *Fusarium moniliforme* and *Trichothecium roseum*. Annals of Biology **1**, 232-234.

SKYLAKAKIS, G. (1981). Effects of alternating and mixing pesticides and the buildup of fungal plant pathogens. *Phytopathology* **71**, 1119-1121.

SKYLAKAKIS, G. (1982). Epidemiological factors affecting the rate of selection of biocide resistant genotypes of plant pathogenic fungi. *Phytopathology* **72**, 271-273.

SNYDER, W. C. & HANSEN, H. N. (1940). The species concept in *Fusarium*. *American Journal of Botany* **27**, 64-67.

SNYDER, W. C. & HANSEN, H. N. (1941). The species concept in *Fusarium* with reference to the section Martiella. *American Journal of Botany* **28**, 738-742.

SNYDER, W. C. & HANSEN, H. N. (1945). The species concept in *Fusarium* with special reference to Discolor and other sections. *American Journal of Botany* **32**, 657-666.

SNYDER, W. C. & HANSEN, H. N. (1954). Variation and speciation in the genus *Fusarium*. *Annales of Academic Science* **60**, 16-23.

STACK, R. W. & McMULLEN, M. P. (1985). Head blighting potential of *Fusarium* species associated with spring barley wheat heads. *Canadian Journal of Plant Pathology* **7**, 79-82.

STAHL, C. (1936). The importance of the germinating speed in the case of cruciferous seeds. *Proceedings of the International Seed Testing Association* **8**, 46-53.

STAUB, T. & SOZZI, D. (1984). Fungicide resistance: A continuing challenge. *Plant Disease* **68**, 1026-1031.

STOVER, R. H. (1962). Fusarial wilt (Panama disease) of bananas and other *Musa* species. *Commonwealth Mycological Institute, Phytopathological* Paper 4, 117 pp.

STRANGE, R. N., MAJER, J. R. & SMITH, H. (1972). Identification of betaine and choline in anthers as the two fungal growth stimulants which explain the susceptibility of wheat to *Fusarium graminearum* at flowering. *Journal of General Microbiology* 73, xviii.

STRANGE, R. N., MAJER, J. R. & SMITH, H. (1974). The isolation and identification of choline and betaine as the two major components in anthers and wheat germ that stimulate *Fusarium graminearum in vitro*. *Transactions of the British Mycological Society* 4(2), 277-290.

STRANGE, R. N. & SMITH, H. (1970). Partial purification and properties of a fungal growth stimulant in anthers which predisposes wheat to attack by *Fusarium graminearum*. *Journal of General Microbiology* 63, X (Abstr.).

STRANGE, R. N. & SMITH, H. (1971a). A rapid assay of fungal growth stimulants *Transactions of the British Mycological Society* 56, 585-588.

STRANGE, R. N. & SMITH, H. (1971b). A fungal stimulant in anthers which predisposes wheat to attack by *Fusarium graminearum*. *Physiological Plant Pathology* 1, 141-150.

STRANGE, R. N. & SMITH, H. (1978a). Effects of choline, betaine and wheat-germ extract on growth of cereal pathogens. *Transactions of the British Mycological Society* 70(2), 193-199.

STRANGE, R. N. & SMITH, H. (1978b). Specificity of choline and betaine as stimulants of *Fusarium graminearum*. *Transactions of the British Mycological Society* 70(2), 187-192.

STRAUSBAUGH, C. A. & MALOY, O. C. (1986). *Fusarium* scab of irrigated wheat in central Washington. *Plant Pathology* 70, 1104-1106.

STURZ, A. V. & JOHNSTON, H. W. (1983). Early colonisation of ears of wheat and barley in *Fusarium poae*. *Canadian Journal of Plant Pathology* 5(2), 107-110.

SUTTON, J. C. (1982). Epidemiology of wheat head blight and maize ear rot caused by *Fusarium graminearum*. *Canadian Journal of Plant Pathology* 4, 195-209.

SWEETS, L. E., PFLEGER, F. L., MORGAN, F. C. & MIZICKO, J. R. (1982). Control of fungi associated with cankers of greenhouse roses. *Plant Disease* 66, 491-494.

SZKOLNIK, M. & GILPATRICK, J. D. (1969). Apparent resistance of *Venturia inaequalis* to dodine in New York apple orchards. *Plant Disease Reporter* 53, 861-864.

SZKOLNIK, M. & GILPATRICK, J. D. (1973). Tolerance of *Venturia inaequalis* to dodine in relation to the history of dodine usage in apple orchards. *Plant Disease Reporter* **57**, 817-821.

TICKLE, J. H. (1974). Aspects of soil contamination with *Fusarium solani* var *coeruleum* and certain pathogens of potato tubers. Ph.D. Thesis, University of Edinburgh.

TIO, M., BURGESS, L. W. NELSON, P. E. & TOUSSOUN, T. A. (1977). Techniques for the isolation, culture and preservation of the *Fusaria*. *Australian Plant Pathology Society Newsletter* **6**, 11-13.

TOTTMAN, D. R., MAKEPEACE, R. J. & BROAD, H. (1979). An explanation of the decimal code for the growth stages of cereals, with illustrations. *Annals of Applied Biology* **93**, 221-234.

TOUSSOUN, T. A. & NELSON, P. E. (1975). Variation and speciation in the *Fusaria*. *Annual Review of Phytopathology* **13**, 71-82.

TOUSSOUN, T. A. & NELSON, P. E. (1976). *A pictorial guide to the identification of Fusarium species according to the taxonomic system of Snyder & Hansen.* 2nd. Edition. University Park: Pennsylvania State University Press, 43 pp.

TU, J. C. (1985). Pink pod of bean caused by *Trichothecium roseum*. *Canadian Journal of Plant Pathology* **7**, 55-57.

TUSA, C., MUNTEANU, I., CAPETT, E., PIRVU, T., BUNESCU, S., SIN, G., NICOLAE, H., TIANU, A., CAEA, D., ROMASCANU, O. & STOICA, V. (1985). Aspects of the *Fusarium* attacks on wheat in Romania. *Review of Plant Pathology* **64(3)**, 1060 (Abstr.).

TVEIT, M. & WOOD, R. K. S. (1955). The control of *Fusarium* blight in oat seedlings with antagonistic species of *Chaetomium*. *Annals of Applied Biology* **43**, 538-552.

UOTI, J. (1976). The effect of fife *Fusarium* spp. on the growth and development of spring wheat and barley. *Annales Agriculturae Fennicae* **15**, 254-262.

VAN DER HOEVEN, E. P. & BOLLEN, G. J. (1972). The effect of benomyl on antagonism towards fungi causing foot rot in rye. *Acta Botanica Neerlandica* **21**, 107-108.

VAKILI, N. G. (1985). Mycoparasitic fungi associated with potential stalk rot pathogens of corn. *Phytopathology* **75**, 1201-1207.

VAN DER HOEVEN, E. P. & BOLLEN, G. J. (1980). Effect of benomyl on soil fungi associated with rye. 1. Effect on the incidence of sharp eyespot caused by *Rhizoctonia cerealis*. *Netherlands Journal of Plant Pathology* **86**, 163-180.

VARGO, R. H. & BAUMER, J. S. (1986). *Fusarium sporothichioides* as pathogen of spring wheat. *Plant Disease* **70**, 629-631.

WAINWRIGHT, A., ROLLETT, A. C. & MORRIS, D. B. (1979). Triadimenol seed treatments for the control of cereal diseases. *Proceedings 1979 British Crop Protection Conference*- Pests and Diseases, 565-574.

WARREN, H. L. & KOMMEDAHL, T. (973). Root-infecting species of *Fusarium* in soil and in the roots, rhizospheres, and residues of oats. *Phytopathology* **63**, 1401-1403.

WARREN, C. G., SANDERS, P. L., COLE, H. & DUICH, J. M. (1977). Relative fitness of benzimidazole- and cadmium-tolerant populations of *Sclerotinia homoecarpa* in the absence and presence of fungicides. *Phytopathology* **67**, 704-708.

WEARING, A. H. (1979). Crown rot of wheat in South Australia. *Australasian Plant Pathology* **8**, 30-31.

WENSLEY, R. N. & McKEEN, C. D. (1962). A soil suspension-plating method of estimating populations of *Fusarium oxysporum* f. *melonis* in muskmelon wilt soils. *Canadian Journal of Microbiology* **8**, 57-64.

WHEELER, B. E. J. (1969). *An introduction to plant diseases*. London: Wiley. 374 pp.

WIESE, M. V. (1977). *Compendium of wheat diseases*. St. Paul, Mn: American Phytopathological Society.

WILCOXSON, R. D., KOMMEDAHL, T., OZMON, E. A. & WINDELS, C. E. (1988). Occurrence of *Fusarium* species in scabby wheat from Minnesota and their pathogenicity to wheat. *Phytopathology* **78(5)**, 586-589.

WILLIAMS, R. J. & AYANABA, A. (1975). Increased incidence of *Pythium* stem rot in cowpeas treated with benomyl and related fungicides. *Phytopathology* **65**, 217-218.

WOLFE, M. S. (1985). Dynamics of the response of barley mildew to the use of sterol synthesis inhibitors. *EPPO Bulletin* **15**, 451-457.

WOLLENWEBER, H. W. & REINKING, O. A. (1935). *Die Fusarien. Ihre Beschreinburg, Schadwirkung und Bekamfung*. Berlin: Paul Parey.

YARHAM, D. J. & GILTRAP, N. J. (1989). Crop diseases in a changing agriculture: arable crops in the UK- a review. *Plant Pathology* **38**, 459-477.

ZADOKS, J. C., CHANG, T. T. & KONZAK, C. F. (1974). A decimal code for the growth stages of cereals. *Weed Research* **14**, 415-421.

ZILLINSKY, F. J. (1983). *Common diseases of small grain cereals*. México: CIMMyT.

APPENDICES

APPENDIX I. Details of formulations and preparation procedures for isolation media used for survey work of Section 2.

The media assessed here have the following formulations-

(a) **PPA medium**- this medium consisted of Difco peptone, 15 g; agar, 20 g; KH_2PO_4, 1.0 g; $MgSO_4.7H_2O$, 0.5 g; streptomycin, 300 ppm; and pentachloronitrobenzene (PCNB), 1:1000 (75% wettable powder). All the ingredients were added to 1 l of distilled water and autoclaved at 121^{o}C for 20 minutes with the exception of streptomycin and PCNB which were added after the medium was cooled down to 48^{o}C. In addition to the streptomycin sulphate (Sigma) recommended by Nash & Snyder (1962) in PPA, chlortetracycline hydrochloride (Sigma), 0.06%, and neomycin sulphate (Sigma), 0.12% were also used to control bacteria and Pythiaceous contamination;

(b) **DCPA-** this medium contained bacteriological peptone (Oxoid), 15 g; KH_2PO_4, 1.0 g; $MgSO_4.7H_2O$, 0.5 g; chloramphenicol, 0.2 g; dichloran (2,6-dichloro-4 nitroalinile) (0.2% solution in ethanol), 1 ml (equivalent to 2 um/ml); agar, 20 g; distilled water to 1.0 l. The medium was sterilised at 121^{o}C for 20 minutes; the final pH was 6.2;

(c) **PDA-** the PDA medium (non-selective) contained potato extract, 4.0 g; dextrose, 20 g; and agar no. 1 (Oxoid), 15.0 g. The materials, in the commercial form, were suspended in 1.0 l of distilled water and sterilised by autoclaving at 121 C for 20 minutes;

(d) **MRB-** this medium was made tap water, 1 l; dextrose, 10 g; peptone, 5 g; KH_2PO_4, 1.0 g; $MgSO_4.7H_2O$, 0.5 g; agar, 20 g; rose bengal, 66 ppm; crystal violet, 10 ppm; streptomycin sulphate, 100 ppm; and sulphuric acid to have a pH 4. Rose bengal and crystal violet were added to the medium with the original ingredients. Sulphuric acid and streptomycin were added after the medium had been melted and cooled sufficiently to be poured on plates (48^{O}C).

Generally 10 ml per 9 cm plastic Petri dish were poured and media prepared 3 to 4 days before use and stored in a cold room at about 4^{O}C.

APPENDICES II-V. Abbreviated analysis of variance tables for the results of fungicide field trials, 1987-1988

Abbreviations

df	degrees of freedom
ms	mean squares
vr	variance ratio
sig	significance
ns	non-significant
*	significant at probability level of P = 0.05
**	significant at probability level of P = 0.01
***	significant at probability level of P = 0.001

APPENDIX II. Bush 1987: percentage frequency of *F. culmorum* and *F. dimerum* on roots and stems of winter barley cv. Igri.

Source of variation	df	Stems ms	Stems vr	Stems sig.	Roots ms	Roots vr	Roots sig.
F. culmorum							
Medium	1	5714	5	ns	2508	12	*
Residual	2	1143			215		
Fungicide	13	2775	9	***	1200	2	*
Fun * Med	13	732	2	*	1406	3	*
Residual	26	320			508		
F. dimerum							
Medium	1	111258	470	**	188108	398	**
Residual	2	237			472		
Fungicide	13	316	1	ns	260	2	ns
Fun * Med	13	277	1	ns	260	2	ns
Residual	26	352			163		

APPENDIX IIIa. Bush 1988: percentage frequency of *F. culmorum, F. dimerum* and *F. sambucinum* on roots and stems of winter barley cv. Magie.

Source of variation	df	Stems ms	Stems vr	Stems sig.	Roots ms	Roots vr	Roots sig.
F. culmorum							
Fungicide	8	802.3	1.6	ns	480.1	0.9	ns
Residual	16	514.5			521.4		
Time	1	6533.3	16.0	***	3223.1	6.2	*
Fun * Time	8	2166.7	5.3	**	944.0	1.8	ns
Residual	18	407.4			516.7		
Medium	1	2503.7	12.8	***	267.6	1.0	ns
Fun * Med	8	132.9	0.7	ns	242.6	0.9	ns
Time * Med	1	33.3	0.2	ns	45.4	0.2	ns
Fun*Ti*Med	8	433.3	2.2	*	120.4	0.5	ns
Residual	36	195.4			264.8		
F. dimerum							
Fungicide	8	160.6	0.6	ns	953.0	5.3	**
Residual	16	265.2			181.5		
Time	1	8533.3	30.7	***	23114.8	80.0	***
Fun * Time	8	258.3	0.9	ns	229.4	0.8	ns
Residual	18	277.8			288.7		
Medium	1	833.3	3.8	ns	1792.6	4.1	*
Fun * Med	8	158.3	0.7	ns	223.8	0.5	ns
Time * Med	1	92.6	0.4	ns	833.3	1.9	ns
Fun*Ti*Med	8	88.4	0.4	ns	277.1	0.6	ns
Residual	36	222.2			435.2		
F. sambucinum							
Fungicide	8	250.2	0.7	ns	126.6	1.3	ns
Residual	16	335.3			99.9		
Time	1	16875.0	48.2	***	1267.6	13.7	**
Fun * Time	8	568.8	1.6	ns	86.3	0.9	ns
Residual	18	350.0			92.6		
Medium	1	1408.3	8.2	**	75.0	1.2	ns
Fun * Med	8	214.6	1.3	ns	85.4	1.3	ns
Time * Med	1	1408.3	8.2	**	8.3	0.1	ns
Fun*Ti*Med	8	181.3	1.1	ns	39.6	0.6	ns
Residual	36	171.3			63.0		

APPENDIX IIIb. Bush 1988: percentage frequency of *F. culmorum, F. dimerum* and *F. sambucinum* on roots and stems of winter barley cv. Plaisant.

Source of variation	df	Stems ms	Stems vr	Stems sig.	Roots ms	Roots vr	Roots sig.
F. culmorum							
Fungicide	8	1184.3	1.5	ns	529.2	1.0	ns
Residual	16	770.4			520.5		
Time	1	8181.5	16.0	***	9823.1	21.1	***
Fun * Time	8	2602.3	5.1	**	444.0	1.0	ns
Residual	18	511.1			466.7		
Medium	1	2903.7	12.4	***	408.3	2.3	ns
Fun * Med	8	319.2	1.7	ns	483.3	2.7	*
Time * Med	1	181.5	0.8	ns	8.3	0.1	ns
Fun*Ti*Med	8	298.1	2.3	ns	158.3	0.9	ns
Residual	36	233.3			177.8		
F dimerum							
Fungicide	8	355.1	2.0	ns	732.2	0.9	ns
Residual	16	179.7			847.8		
Time	1	11000.9	72.9	***	18148.1	15.9	***
Fun * Time	8	113.4	0.8	ns	525.2	0.5	ns
Residual	18	150.9			1144.4		
Medium	1	675.0	3.2	ns	1481.5	3.8	ns
Fun * Med	8	487.5	2.3	*	221.1	0.6	ns
Time * Med	1	208.3	1.0	ns	3.7	0.1	ns
Fun*Ti*Med	8	354.2	1.7	ns	605.8	1.6	ns
Residual	36	209.3			388.9		
F. sambucinum							
Fungicide	8	116.2	0.5	ns	58.3	0.4	ns
Residual	16	221.4			155.2		
Time	1	4800.0	31.3	***	1337.0	6.9	*
Fun * Time	8	41.7	0.3	ns	87.0	0.5	ns
Residual	18	153.6			192.6		
Medium	1	533.3	9.8	**	33.3	0.2	ns
Fun * Med	8	75.0	1.4	ns	12.5	0.3	ns
Time * Med	1	1200.0	22.0	***	33.3	0.2	ns
Fun*Ti*Med	8	87.5	1.6	ns	70.8	0.5	ns
Residual	36	54.6			154.6		

APPENDIX IIIc. Borders 1988: percentage frequency of *F. culmorum, F. dimerum* and *F. sambucinum* on roots and stems of winter barley cv. Magie.

Source of variation	df	Stems ms	Stems vr	Stems sig.	Roots ms	Roots vr	Roots sig.
F. culmorum							
Fungicide	8	2252.3	6.9	***	119.0	0.5	ns
Residual	16	328.7			219.7		
Time	1	12245.4	33.0	***	408.3	2.3	ns
Fun * Time	8	3099.5	8.3	***	87.5	0.5	ns
Residual	18	371.3			178.7		
Medium	1	334.3	1.7	ns	23.1	0.1	ns
Fun * Med	8	280.1	1.4	ns	181.5	1.0	ns
Time * Med	1	23.1	0.1	ns	675.0	3.5	ns
Fun*Ti*Med	8	294.0	1.5	ns	216.7	1.1	ns
Residual	36	197.2			190.7		
F. dimerum							
Fungicide	8	545.4	1.9	ns	742.6	1.1	ns
Residual	16	283.2			692.6		
Time	1	25514.8	61.0	***	20833.3	35.5	***
Fun * Time	8	169.0	0.4	ns	558.3	1.0	ns
Residual	18	418.5			586.1		
Medium	1	1481.5	5.2	*	1633.3	2.8	ns
Fun * Med	8	389.8	1.4	ns	300.0	0.5	ns
Time * Med	1	14.8	0.1	ns	2314.8	4.0	ns
Fun*Ti*Med	8	302.3	1.1	ns	564.8	1.0	ns
Residual	36	282.4			384.3		
F. sambucinum							
Fungicide	8	587.0	2.3	ns	514.6	6.3	***
Residual	16	252.0			81.9		
Time	1	14467.6	87.8	***	6689.8	90.3	***
Fun * Time	8	630.1	3.8	**	612.7	8.3	***
Residual	18	164.8			74.1		
Medium	1	1134.3	6.4	*	112.0	1.0	ns
Fun * Med	8	180.1	1.0	ns	10.0	0.1	ns
Time * Med	1	1134.3	6.4	*	208.3	1.8	ns
Fun*Ti*Med	8	184.3	1.0	ns	39.6	0.3	ns
Residual	36	176.9			114.8		

APPENDIX IIId. Borders 1988: percentage frequency of *F. culmorum, F. dimerum* and *F. sambucinum* on roots and stems of winter barley cv. Plaisant.

Source of variation	df	Stems ms	Stems vr	Stems sig.	Roots ms	Roots vr	Roots sig.
F. culmorum							
Fungicide	8	526.6	1.2	ns	429.2	1.2	ns
Residual	16	426.3			355.2		
Time	1	267.6	0.9	ns	1008.3	2.0	ns
Fun * Time	8	403.0	1.4	ns	225.0	0.4	ns
Residual	18	290.7			514.8		
Medium	1	675.0	2.7	ns	75.0	0.3	ns
Fun * Med	8	97.7	0.4	ns	145.8	0.5	ns
Time * Med	1	23.1	0.1	ns	75.0	0.3	ns
Fun*Ti*Med	8	66.9	0.3	ns	319.7	1.4	ns
Residual	36	248.1			288.9		
F. dimerum							
Fungicide	8	233.3	0.4	ns	422.9	0.5	ns
Residual	16	577.1			929.2		
Time	1	34133.3	125	***	8533.3	11.4	**
Fun * Time	8	404.2	1.5	ns	406.3	0.5	ns
Residual	18	274.1			750.9		
Medium	1	3333.3	12.3	***	4800.0	11.3	**
Fun * Med	8	212.5	0.8	ns	481.3	1.1	ns
Time * Med	1	2503.7	9.2	**	1792.6	4.2	*
Fun*Ti*Med	8	412.0	1.5	ns	632.2	1.5	ns
Residual	36	271.3			425.0		
F. sambucinum							
Fungicide	8	895.4	1.8	ns	114.8	0.7	ns
Residual	16	504.1			163.4		
Time	1	31689.9	50.0	***	2700.0	14.4	***
Fun * Time	8	585.6	0.9	ns	58.3	0.3	ns
Residual	18	633.3			188.0		
Medium	1	4408.3	12.5	***	14.8	0.1	ns
Fun * Med	8	433.3	1.2	ns	73.1	0.6	ns
Time * Med	1	2045.4	5.8	*	92.6	0.7	ns
Fun*Ti*Med	8	174.5	0.5	ns	119.6	0.9	ns
Residual	36	353.7			129.6		

APPENDIX IIIe. Fife 1988: percentage frequency of *F. culmorum*, *F. dimerum* and *F. nivale* on roots and stems of winter barley cv. Magie.

Source of variation	df	Stems ms	Stems vr	Stems sig.	Roots ms	Roots vr	Roots sig.
F. culmorum							
Fungicide	8	6569.1	14.9	***	1399.2	4.2	**
Residual	16	440.9			334.0		
Time	2	2289.5	5.3	**	2639.5	8.4	***
Fun * Time	16	3263.8	7.6	***	612.4	1.4	*
Residual	36	429.6			315.4		
Medium	1	5000.0	17.7	***	800.0	6.1	*
Fun * Med	8	413.9	1.5	ns	51.4	0.4	ns
Time * Med	2	2646.3	9.4	***	451.9	3.4	*
Fun*Ti*Med	16	366.4	1.3	ns	92.8	0.7	ns
Residual	54	282.1			131.5		
F. dimerum							
Fungicide	8	952.5	3.0	*	1580.2	3.1	*
Residual	16	318.0			517.5		
Time	2	8285.8	27.5	***	1359.9	2.3	ns
Fun * Time	16	569.8	1.9	ns	403.6	0.7	ns
Residual	36	301.2			583.0		
Medium	1	417.3	1.4	ns	298.8	0.7	ns
Fun * Med	8	322.8	1.1	ns	687.7	1.6	ns
Time * Med	2	2052.5	6.9	**	541.4	1.3	ns
Fun*Ti*Med	36	360.1	1.2	ns	378.2	0.9	ns
Residual	54	298.8			430.9		
F. nivale							
Fungicide	8	786.7	5.4	**	313.6	1.3	ns
Residual	16	146.7			233.5		
Time	2	5093.2	11.9	***	239.5	5.2	*
Fun * Time	16	475.2	1.1	ns	102.0	2.2	*
Residual	36	426.2			46.0		
Medium	1	2222.2	6.9	*	50.0	0.6	ns
Fun * Med	8	533.3	1.7	ns	88.9	1.2	ns
Time * Med	2	57.4	0.2	ns	7.4	0.1	ns
Fun*Ti*Med	16	122.7	0.4	ns	50.5	0.7	ns
Residual	54	321.0			75.3		

APPENDIX IIIf. Fife 1988: percentage frequency of *F. culmorum*, *F. dimerum* and *F. nivale* on roots and stems of winter barley cv. Plaisant.

Source of variation	df	Stems ms	Stems vr	Stems sig.	Roots ms	Roots vr	Roots sig.
F. culmorum							
Fungicide	8	2108.0	5.6	**	728.9	2.7	*
Residual	16	375.4			271.5		
Time	2	504.3	1.4	ns	106.2	0.4	ns
Fun * Time	16	1449.5	4.0	***	464.5	1.6	ns
Residual	36	363.0			287.7		
Medium	1	2372.8	11.0	**	0.0	0.0	ns
Fun * Med	8	403.4	1.9	ns	68.1	0.3	ns
Time * Med	2	363.6	1.7	ns	88.9	0.3	ns
Fun*Ti*Med	36	200.4	0.9	ns	206.9	0.8	ns
Residual	54	216.0			258.6		
F. dimerum							
Fungicide	8	371.9	0.6	ns	724.2	1.1	ns
Residual	16	665.9			647.1		
Time	2	26130.3	39.1	***	1193.2	3.3	*
Fun * Time	16	459.4	0.7	ns	800.8	2.2	*
Residual	36	668.2			364.8		
Medium	1	484.0	1.4	ns	417.3	0.7	ns
Fun * Med	8	464.5	1.3	ns	546.5	0.9	ns
Time * Med	2	4122.8	11.5	***	3719.1	6.3	**
Fun*Ti*Med	36	315.9	0.9	ns	483.7	0.8	ns
Residual	54	357.4			595.1		
F. nivale							
Fungicide	8	301.4	0.7	ns	49.7	0.8	ns
Residual	16	405.6			63.8		
Time	2	2150.0	7.5	**	106.2	1.6	ns
Fun * Time	16	443.1	1.6	ns	69.4	1.0	ns
Residual	36	285.5			67.0		
Medium	1	450.0	1.5	ns	30.3	0.4	ns
Fun * Med	8	281.9	0.9	ns	83.0	1.2	ns
Time * Med	2	338.9	1.1	ns	2.5	0.1	ns
Fun*Ti*Med	36	304.2	1.0	ns	44.8	0.6	ns
Residual	54	300.0			69.1		

APPENDIX IIIg. Bush 1988: percentage frequency of *F. culmorum F. nivale, F. avenaceum, Epicoccum, Cladosporium* and *Alternaria* on ears of winter barley.

CV. MAGIE

Source of variation	**df**	**ms**	**vr**	**sig.**	**ms**	**vr**	**sig.**
		F. culmorum			*F. nivale*		
Fungicide	8	1.9	2.0	ns	6.5	2.1	ns
Residual	16	0.9			3.1		
		F. avenaceum			*Epicoccum*		
Fungicide	8	552.0	2.1	ns	88.1	1.0	ns
Residual	16	268.2			90.1		
		Cladosporium			*Alternaria*		
Fungicide	8	110.0	0.7	ns	24.2	1.0	ns
Residual	16	151.3			23.9		

CV. PLAISANT

		F. culmorum			*F.nivale*		
Fungicide	8	26.7	0.7	ns	6.5	1.0	ns
Residual	16	37.9			6.5		
		F. avenaceum			*Epicoccum*		
Fungicide	8	1286.8	5.9	***	47.2	1.2	ns
Residual	16	217.7			39.2		
		Cladosporium			*Alternaria*		
Fungicide	8	170.2	1.4	ns	73.9	1.5	ns
Residual	16	122.3			49.5		

APPENDIX IIIh. Borders 1988: percentage frequency of *F. culmorum Epicoccum, Cladosporium, Alternaria* and *Septoria* on ears of winter barley.

CV. MAGIE

Source of Variation	df	ms	vr	sig.	ms	vr	sig.
		F. culmorum			*Epicoccum*		
Fungicide	8	628.2	5.5	**	27.0	0.7	ns
Residual	16	114.1			39.2		
		Alternaria			*Cladosporium*		
Fungicide	8	34.1	0.5	ns	145.8	1.0	ns
Residual	16	71.6			151.6		
		Septoria					
Fungicide	8	188.9	2.4	ns			
Residual	16	79.2					

CV. PLAISANT

Source of Variation	df	ms	vr	sig.	ms	vr	sig.
		F. culmorum			*Epicoccum*		
Fungicide	8	114.6	1.4	ns	27.8	0.5	ns
Residual	16	85.6			53.2		
		Alternaria			*Cladosporium*		
Fungicide	8	36.5	1.2	ns	230.6	1.1	ns
Residual	16	30.8			214.2		
		Septoria					
Fungicide	8	27.3	1.7	ns			
Residual	16	16.4					

APPENDIX IIIi. Fife 1988: percentage frequency of *F. culmorum, F. nivale, Epicoccum, Cladosporium, Alternaria* and *Septoria* on ears of winter barley.

CV. MAGIE

Source of variation	df	ms	vr	sig.	ms	vr	sig.
		F. culmorum			*F. nivale*		
Fungicide	8	515.0	2.0	ns	443.1	5.1	**
Residual	16	252.6			87.6		
Time	1	41.7	0.4	ns	7878.8	43.5	***
Fun * Ti	8	74.2	0.7	ns	327.2	1.8	ns
Residual	18	104.5			181.3		
		Epicoccum			*Cladosporium*		
Fungicide	8	70.2	2.7	*	580.4	3.6	*
Residual	16	25.8			159.6		
Time	1	157.0	1.7	ns	229.4	0.9	ns
Fun * Ti	8	29.5	0.3	ns	208.9	0.8	ns
Residual	18	95.1			257.5		
		Alternaria			*Septoria*		
Fungicide	8	43.8	4.3	**	144.0	1.8	ns
Residual	16	10.1			79.3		
Time	1	3072.7	35.3	***	154.6	10.5	**
Fun * Ti	8	41.1	0.5	ns	14.8	1.0	ns
Residual	18	86.9			14.7		

CV. PLAISANT

Source of variation	df	ms	vr	sig.	ms	vr	sig.
		F. culmorum			*F. nivale*		
Fungicide	8	1494.0			217.8	2.2	ns
Residual	16	242.1	6.2	***	100.8		
Time	1	217.9	3.5	ns	3990.3	26.2	***
Fun * Ti	8	8.2	0.1	ns	199.5	1.3	ns
Residual	18	62.5			152.5		
		Epicoccum			*Cladosporium*		
Fungicide	8	147.2	0.7	ns	143.6	1.8	ns
Residual	16	201.4			81.0		
Time	1	5036.8	27.4	***	106.1	1.1	ns
Fun * Ti	8	250.2	1.4	ns	136.6	1.4	ns
Residual	18	183.6			98.2		
		Alternaria			*Septoria*		
Fungicide	8	104.8	0.7	ns	119.4	0.5	ns
Residual	16	159.3			265.9		
Time	1	114.9	0.9	ns	1777.4	64.5	***
Fun * Ti	8	61.1	0.5	ns	34.1	1.2	ns
Residual	18	131.5			27.6		

APPENDIX IVa. Bush 1987: percentage frequency of *F. culmorum*, *F. dimerum*, *F. poae* and *F. avenaceum* on roots and stems of spring barley cvs. Golf and Golden Promise.

Source of variation	df	Stems ms	Stems vr	Stems sig.	Roots ms	Roots vr	Roots sig.
F. culmorum							
Fungicide	10	3889.3	51.5	***	5155.6	45.3	***
Residual	10	75.5			113.7		
Time	1	82045.5	538.8	***	12955.1	70.2	***
Fun * Time	10	495.5	3.3	*	867.6	4.7	**
Residual	11	152.3			184.7		
Medium	1	8181.8	72.7	***	777.8	3.6	ns
Fun * Med	10	1516.8	13.5	***	1710.3	7.9	***
Time * Med	1	9.1	0.1	ns	1477.8	6.8	*
Fun*Ti*Med	10	1271.6	11.3	***	187.8	0.9	ns
Residual	22	112.5			**217.6**		
F. dimerum							
Fungicide	10	882.3	5.5	**	607.3	3.2	*
Residual	10	159.8			187.5		
Time	1	2550.6	16.8	**	16036.4	110.3	***
Fun * Time	10	839.3	5.5	**	348.9	2.4	ns
Residual	11	151.7			145.5		
Medium	1	11946.0	47.2	***	11456.8	32.2	***
Fun * Med	10	1107.3	4.4	**	489.3	1.4	ns
Time * Med	1	18614.2	73.6	***	8456.8	23.8	***
Fun*Ti*Med	10	1038.0	4.1	**	636.8	1.8	ns
Residual	22	252.8			**355.7**		
F. poae							
Fungicide	10	96.3	4.8	*	88.9	1.6	**ns**
Residual	10	20.1			**54.8**		
Time	1	36.4	0.8	ns	618.8	10.6	**
Fun * Time	10	82.6	1.7	ns	82.5	1.4	ns
Residual	11	44.3			**58.5**		
Medium	1	9.1	0.3	ns	164.2	3.2	ns
Fun * Med	10	50.3	1.5	ns	60.5	1.2	ns
Time * Med	1	227.3	6.9	*	164.2	3.2	ns
Fun*Ti*Med	10	78.5	2.4	*	110.5	2.2	ns
Residual	22	33.0			**51.7**		
F. avenaceum							
Fungicide	10	150.6	3.7	*	31.6	2.1	ns
Residual	10	40.6			14.8		
Time	1	96.0	1.2	ns	227.3	14.3	**
Fun * Time	10	166.0	2.1	ns	62.3	3.9	*
Residual	11	77.8			15.9		
Medium	1	127.8	2.9	ns	81.8	5.5	*
Fun * Med	10	247.8	5.7	***	81.8	5.5	***
Time * Med	1	618.8	14.1	***	36.4	2.5	ns
Fun*Ti*Med	10	123.8	2.9	*	73.9	5.0	***
Residual	22	43.8			14.8		

APPENDIX IVb. Bush 1988: percentage frequency of *F. culmorum*, *F. dimerum*, *F. sambucinum* on roots and stems of spring barley cvs. Golf and Golden Promise.

Source of variation	df	Stems ms	Stems vr	Stems sig.	Roots ms	Roots vr	Roots sig.
F. culmorum							
Fungicide	10	8334.5	20.1	***	4234.8	12.1	***
Residual	30	414.0			349.4		
Time	2	137586.8	247.2	***	72648.1	88.1	***
Fun * Time	20	2692.6	4.8	***	1986.4	2.4	**
Residual	66	556.7			824.9		
Medium	1	733.3	6.1	*	9.5	0.1	ns
Fun * Med	10	184.2	1.5	ns	202.0	0.9	ns
Time * Med	2	432.2	3.6	*	654.9	3.0	*
Fun*Ti*Med	20	118.0	1.0	ns	149.9	0.7	ns
Residual	99	120.2			216.3		
F. dimerum							
Fungicide	10	156.2	1.1	ns	1454.5	2.9	*
Residual	30	142.4			505.5		
Time	2	9291.3	73.4	***	10542.0	19.1	***
Fun * Time	20	83.4	0.7	ns	946.6	2.4	*
Residual	66	126.5			551.8		
Medium	1	909.5	9.6	**	276.1	0.7	ns
Fun * Med	10	123.6	1.3	ns	339.5	0.9	ns
Time * Med	2	979.9	10.3	***	635.2	1.7	ns
Fun*Ti*Med	20	67.8	0.7	ns	382.3	1.0	ns
Residual	99	94.8			378.4		
F. sambicunum							
Fungicide	10	403.2	1.5	ns	272.7	1.1	ns
Residual	30	266.0			238.6		
Time	2	591.3	1.7	ns	754.9	3.2	*
Fun * Time	20	335.5	1.0	ns	239.1	1.0	ns
Residual	66	341.0			234.0		
Medium	1	30.7	0.6	ns	3.4	0.1	ns
Fun * Med	10	73.2	1.4	ns	30.9	1.0	ns
Time * Med	2	21.6	0.4	ns	8.0	0.3	ns
Fun*Ti*Med	20	101.6	2.0	*	50.5	1.6	ns
Residual	99	50.6			31.4		

APPENDIX IVc. Borders 1988: percentage frequency of *F. culmorum*, *F. dimerum*, *F. sambucinum* on roots and stems of spring barley cvs. Golf and Golden Promise.

Source of variation	df	Stems ms	Stems vr	Stems sig.	Roots ms	Roots vr	Roots sig.
F. culmorum							
Fungicide	7	7113.3	13.7	***	476.8	1.6	ns
Residual	21	518.9			295.5		
Time	1	25594.5	32.8	***	6903.1	24.7	***
Fun * Time	7	1003.5	1.3	ns	478.1	1.7	ns
Residual	24	779.4			279.2		
Medium	1	3100.8	12.5	***	3.1	0.1	ns
Fun * Med	7	295.4	1.2	ns	35.3	0.3	ns
Time * Med	1	19.5	0.1	ns	0.0	0.0	ns
Fun*Ti*Med	7	217.7	0.9	ns	35.7	0.3	ns
Residual	48	248.7			114.6		
F. dimerum							
Fungicide	7	301.8	0.6	ns	1780.2	1.7	ns
Residual	21	479.5			1019.2		
Time	1	1800.0	3.8	ns	25594.5	33.8	***
Fun * Time	7	1632.1	3.4	*	548.1	0.7	ns
Residual	24	476.0			758.1		
Medium	1	528.1	2.5	ns	225.8	0.8	ns
Fun * Med	7	388.8	1.8	ns	407.9	1.5	ns
Time * Med	1	1128.1	5.3	*	2194.5	8.1	**
Fun*Ti*Med	7	81.7	0.4	ns	651.7	2.4	*
Residual	48	213.5			271.1		
F. nivale							
Fungicide	7	152.6	2.1	ns	146.0	1.1	ns
Residual	21	71.0			125.7		
Time	1	94.5	1.5	ns	12.5	0.1	ns
Fun * Time	7	194.5	3.1	*	273.2	2.2	ns
Residual	24	63.3			121.9		
Medium	1	175.8	7.1	*	153.1	2.1	ns
Fun * Med	7	32.9	1.3	ns	35.3	0.5	ns
Time * Med	1	19.5	0.8	ns	112.5	1.5	ns
Fun*Ti*Med	7	48.1	1.9	ns	41.1	0.6	ns
Residual	48	24.7			72.9		
F. sambucinum							
Fungicide	7	16.1	1.0	ns	6.1	1.2	ns
Residual	21	16.7			4.9		
Time	1	50.0	3.0	ns	7.0	1.4	ns
Fun * Time	7	21.4	1.3	ns	14.2	2.9	*
Residual	24	16.7			4.9		
Medium	1	28.1	4.9	*	0.8	0.1	ns
Fun * Med	7	3.1	0.5	ns	4.4	0.5	ns
Time * Med	1	3.1	0.5	ns	0.8	0.1	ns
Fun*Ti*Med	7	10.3	1.8	ns	4.4	0.5	ns
Residual	48	5.7			8.1		

APPENDIX IVd. Fife 1988: percentage frequency of *F. culmorum*, *F. dimerum*, *F. sambucinum* on roots and stems of spring barley cvs. Golf and Golden Promise.

Source of variation	df	Stems ms	Stems vr	Stems sig.	Roots ms	Roots vr	Roots sig.
F. culmorum							
Fungicide	12	685.3	1.1	ns	1050.5	2.1	ns
Residual	24	612.5			493.2		
Time	1	21000.6	34.3	***	12564.1	22.5	***
Fun * Time	12	1022.9	1.7	ns	826.6	1.5	ns
Residual	26	611.5			558.3		
Medium	1	16.0	0.1	ns	23.1	0.1	ns
Fun * Med	12	282.7	1.2	ns	149.5	0.9	ns
Time * Med	1	5.8	0.1	ns	164.1	0.9	ns
Fun*Ti*Med	12	261.3	0.1	ns	212.7	0.2	ns
Residual	52	242.3			174.4		
F. dimerum							
Fungicide	12	674.1	2.7	*	1338.9	1.3	ns
Residual	24	250.4			1005.2		
Time	1	4102.6	6.6	*	27467.3	26.4	***
Fun * Time	12	305.3	0.5	ns	925.6	0.9	ns
Residual	26	624.4			1040.4		
Medium	1	23.1	0.1	ns	2385.3	5.7	*
Fun * Med	12	425.9	1.9	ns	765.8	1.8	ns
Time * Med	1	64.1	0.3	ns	1939.1	4.6	*
Fun*Ti*Med	12	111.3	0.5	ns	841.9	2.0	*
Residual	52	226.3			421.8		
F. nivale							
Fungicide	12	562.7	3.3	**	66.1	0.8	ns
Residual	24	169.4			82.0		
Time	1	2708.3	9.6	**	31.4	0.3	ns
Fun * Time	12	645.8	2.3	*	96.7	0.9	ns
Residual	26	281.4			109.0		
Medium	1	51.9	0.6	ns	51.9	0.6	ns
Fun * Med	12	50.5	0.6	ns	97.8	1.1	ns
Time * Med	1	51.9	0.6	ns	16.0	0.2	ns
Fun*Ti*Med	12	53.3	0.7	ns	92.4	1.0	ns
Residual	52	80.8			90.4		
F. sambucinum							
Fungicide	12	130.8	0.7	ns	23.1	0.9	ns
Residual	24	177.1			29.3		
Time	1	2464.1	17.0	***	31.4	0.9	ns
Fun * Time	12	172.4	1.2	ns	31.4	0.9	ns
Residual	26	144.9			33.3		
Medium	1	656.4	3.5	*	144.2	5.0	*
Fun * Med	12	142.6	0.8	ns	19.2	0.7	ns
Time * Med	1	925.6	4.9	*	5.8	0.2	ns
Fun*Ti*Med	12	109.0	0.6	ns	22.8	0.8	ns
Residual	52	188.5			28.9		

APPENDIX IVe. Trial sites, 1988: percentage frequency of *Fusarium* and other species on ears of spring barley cvs. Golf and Golden Promise.

BUSH

Source of variation	df	ms	vr	sig.	ms	vr	sig.
		F. culmorum			*F. avenaceum*		
Fungicide	10	214.1	1.2	ns	793.2	6.4	***
Residual	30	180.6			123.0		
Time	1	18176.4	112.2	***	100.0	1.1	ns
Fun * Ti	10	184.1	1.2	ns	118.8	1.3	ns
Residual	33	162.0			90.9		
		Epicoccum			*Botrytis*		
Fungicide	10	376.2	2.0	ns	145.9	0.6	ns
Residual	30	192.3			259.2		
Time	1	1773.2	9.1	**	593.3	2.4	ns
Fun * Ti	10	123.0	0.6	ns	156.1	0.6	ns
Residual	33	194.5			249.0		
		T. roseum					
Fungicide	10	101.6	1.2	ns			
Residual	30	84.1					
Time	1	20309.6	287.3	***			
Fun * Ti	10	135.8	1.9	ns			
Residual	30	70.7					

BORDERS

		F. culmorum			*F. nivale*		
Fungicide	10	152.2	1.3	ns	4.7	0.3	ns
Residual	30	114.4			15.8		
		F. avenaceum			*F. sambucinum*		
Fungicide	10	19.0	1.1	ns	78.9	1.1	ns
Residual		16.9			71.1		

FIFE

		F. culmorum			*F. avenaceum*		
Fungicide	12	199.1	1.1	ns	4.8	1.3	ns
Residual	24	184.5			3.7		
		F. nivale			*Cladosporium*		
Fungicide	12	2086.2	7.7	***	251.6	0.6	ns
Residual	24	269.4			391.0		
		Epicoccum					
Fungicide	12	1044.4	2.0	ns			
Residual	24	510.1					

APPENDIX Va. Fife 1987: percentage frequency of *F. culmorum*, *F. dimerum*, *F. avenaceum*, *F. poae,* and on roots and stems of winter wheat cv. Avalon.

Source of variation	df	Stems ms	Stems vr	Stems sig.	Roots ms	Roots vr	Roots sig.
F. culmorum							
Fungicide	9	4001.1	7.1	***	1903.4	8.5	***
Residual	27	561.3			225.1		
Time	1	36602.5	58.3	***	14630.6	45.0	***
Fun * Time	9	701.1	1.1	ns	166.7	0.5	ns
Residual	30	627.9			324.8		
Medium	1	90.0	0.4	ns	0.6	0.01	ns
Fun * Med	9	266.4	1.2	ns	120.1	0.9	ns
Time * Med	1	640.0	2.8	ns	30.6	0.2	ns
Fun*Ti*Med	9	227.5	1.0	ns	64.0	0.5	ns
Residual	60	232.1			132.7		
F. dimerum							
Fungicide	9	572.2	1.2	ns	504.2	0.6	ns
Residual	27	491.7			810.9		
Time	1	1690.0	2.4	ns	2805.6	1.2	ns
Fun * Time	9	744.2	1.0	ns	1459.8	0.6	ns
Residual	30	718.8			2322.7		
Medium	1	1102.5	2.7	ns	7425.6	15.6	***
Fun * Med	9	398.3	1.0	ns	160.3	0.3	ns
Time * Med	1	7840.0	19.5	***	8850.6	18.6	***
Fun*Ti*Med	9	563.6	1.4	ns	460.3	1.0	ns
Residual	60	401.7			476.5		
F. avenaceum							
Fungicide	9	128.1	0.7	ns	50.0	1.1	ns
Residual	27	173.9			46.1		
Time	1	50.6	0.2	ns	122.5	2.2	ns
Fun * Time	9	274.2	0.9	ns	36.4	0.6	ns
Residual	30	301.9			56.7		
Medium	1	15.6	0.5	ns	0.0	0.0	ns
Fun * Med	9	61.5	1.9	ns	2.8	0.4	ns
Time * Med	1	5.6	0.2	ns	2.5	0.4	ns
Fun*Ti*Med	9	26.5	0.9	ns	8.1	1.2	ns
Residual	60	32.3			6.7		
F. poae							
Fungicide	9	320.9	1.0	ns	334.8	0.9	ns
Residual	27	310.4			373.9		
Time	1	5.6	0.02	ns	6375.6	8.9	**
Fun * Time	9	357.0	1.2	ns	382.6	0.5	ns
Residual	30	300.3			715.2		
Medium	1	5.6	0.1	ns	5.6	0.03	ns
Fun * Med	9	120.9	2.0	ns	54.2	0.3	ns
Time * Med	1	0.6	0.01	ns	5.6	0.03	ns
Fun*Ti*Med	9	60.4	1.0	ns	101.5	0.6	ns
Residual	60	60.2			175.6		

APPENDIX Vb. Fife 1988: percentage frequency of *F. culmorum*, *F. dimerum*, *F. avenaceum*, *F. sambucinum* and *F. nivale* on roots and stems of winter wheat cv. Avalon.

Source of variation	df	Stems ms	vr	sig.	Roots ms	vr	sig.
F. culmorum							
Fungicide	9	6453.1	15.1	***	3214.2	6.2	***
Residual	27	427.8			520.7		
Time	1	12075.6	24.3	***	1755.6	4.0	*
Fun * Time	9	1149.2	2.3	*	545.9	1.2	ns
Residual	30	496.9			438.5		
Medium	1	1500.6	6.4	*	525.6	3.0	ns
Fun * Med	9	193.7	0.8	ns	127.0	0.7	ns
Time * Med	1	0.0	0.0	ns	105.6	0.6	ns
Fun*Ti*Med	9	116.0	0.5	ns	45.9	0.3	ns
Residual	60	236.0			174.4		
F. dimerum							
Fungicide	9	114.5	1.1	ns	603.9	1.2	ns
Residual	27	101.7			487.8		
Time	1	1890.6	13.6	***	9302.5	14.3	***
Fun * Time	9	74.0	0.5	ns	391.4	0.6	ns
Residual	30	139.0			650.8		
Medium	1	180.6	1.7	ns	16000.0	40.6	***
Fun * Med	9	230.6	2.1	*	725.0	1.8	ns
Time * Med	1	105.6	1.0	ns	2102.5	5.3	*
Fun*Ti*Med	9	114.0	1.1	ns	113.6	0.3	ns
Residual	60	107.7			394.2		
F. avenaceum							
Fungicide	9	317.8	1.0	ns	154.2	1.3	ns
Residual	27	306.9			119.2		
Time	1	9610.0	24.6	***	1000.0	8.7	**
Fun * Time	9	269.7	0.7	ns	154.2	1.3	ns
Residual	30	390.4			115.4		
Medium	1	1322.5	5.8	*	10.0	0.1	ns
Fun * Med	9	87.8	0.4	ns	50.3	0.5	ns
Time * Med	1	1690.0	7.4	**	10.0	0.1	ns
Fun*Ti*Med	9	44.2	0.2	ns	50.3	0.5	ns
Residual	60	288.3			92.9		
F. sambucinum							
Fungicide	9	548.9	2.7	*	220.9	0.9	ns
Residual	27	200.0			235.5		
Time	1	21622.5	75.6	***	4038.9	21.4	***
Fun * Time	9	557.2	2.0	ns	184.6	1.0	ns
Residual	30	287.4			188.7		
Medium	1	122.5	0.9	ns	25.7	0.2	ns
Fun * Med	9	348.9	2.6	*	237.7	1.6	ns
Time * Med	1	562.5	4.2	*	15.8	0.1	ns
Fun*Ti*Med	9	230.6	1.7	ns	76.7	0.5	ns
Residual	60	133.3			149.8		
F. nivale							
Fungicide	9	105.6	5.6	***	389.4	5.6	***
Residual	27	19.0			69.0		
Time	1	105.6	5.6	*	380.8	5.3	*
Fun * Time	9	105.6	5.6	***	416.4	5.8	***
Residual	30	19.0			71.8		
Medium	1	0.6	0.1	ns	0.8	0.1	ns
Fun * Med	9	0.6	0.1	ns	16.7	1.3	ns
Time * Med	1	0.6	0.1	ns	0.2	0.01	ns
Fun*Ti*Med	9	0.6	0.1	ns	7.3	0.6	ns
Residual	60	7.3			13.2		

APPENDIX Vc. Borders 1988: percentage frequency of *F. culmorum*, *F. dimerum*, *F. nivale* and *F. sambucinum* on roots and stems of winter wheat cv. Longsbow.

Source of variation	df	Stems ms	Stems vr	Stems sig.	Roots ms	Roots vr	Roots sig.
F. culmorum							
Fungicide	9	11572.5	36.2	***	4706.2	10.3	***
Residual	27	319.4			458.6		
Time	1	54760.0	139.5	***	680.6	1.3	ns
Fun * Time	9	1629.4	4.2	***	1219.5	2.4	*
Residual	30	392.5			517.3		
Medium	1	4000.0	24.1	***	30.6	0.2	ns
Fun * Med	9	200.0	1.2	ns	514.0	2.5	*
Time * Med	1	1322.5	8.0	**	140.6	0.7	ns
Fun*Ti*Med	9	169.7	1.0	ns	426.7	2.1	ns
Residual	60	165.8			203.5		
F. dimerum							
Fungicide	9	105.3	1.7	ns	575.6	1.1	ns
Residual	27	60.3			531.4		
Time	1	90.0	0.9	ns	43230.6	105.3	***
Fun * Time	9	49.7	0.5	ns	247.3	0.6	ns
Residual	30	100.4			410.6		
Medium	1	160.0	2.4	ns	6375.6	19.8	***
Fun * Med	9	125.3	1.9	ns	347.8	1.1	ns
Time * Med	1	10.0	0.2	ns	6375.6	19.8	***
Fun*Ti*Med	9	25.3	0.4	ns	178.4	0.6	ns
Residual	60	66.3			322.7		
F. nivale							
Fungicide	9	403.4	1.3	ns	553.9	2.8	*
Residual	27	322.5			197.4		
Time	1	275.6	2.0	ns	360.0	1.5	ns
Fun * Time	9	281.2	2.1	ns	685.0	2.9	*
Residual	30	135.6			234.2		
Medium	1	330.6	5.3	*	2.5	0.1	ns
Fun * Med	9	105.6	1.7	ns	119.2	2.0	ns
Time * Med	1	5.6	0.1	ns	202.5	3.3	ns
Fun*Ti*Med	9	22.3	0.4	ns	174.7	2.9	**
Residual	60	62.7			60.8		
F. sambucinum							
Fungicide	9	339.5	2.1	ns	65.0	0.8	**ns**
Residual	27	162.3			77.8		
Time	1	2805.6	10.9	**	360.0	4.4	*
Fun * Time	9	230.6	0.9	ns	68.3	0.8	**ns**
Residual	30	258.1			82.5		
Medium	1	600.6	3.3	ns	10.0	0.4	ns
Fun * Med	9	131.2	0.7	ns	35.0	1.6	ns
Time * Med	1	1890.6	10.5	**	0.0	0.0	ns
Fun*Ti*Med	9	212.8	1.2	ns	25.0	0.1	ns
Residual	60	179.4			22.5		

APPENDIX Vd. Trial sites, 1988: percentage frequency of *F. culmorum, F. nivale, F. avenaceum Epicoccum, Cladosporium* and *Alternaria* on ears of winter wheat cv Longsbow.

BORDERS

Source of variation	df	ms	vr	sig.	ms	vr	sig.
		F. culmorum			*F. nivale*		
Fungicide	9	2594.3	15.5	***	348.6	2.7	*
Residual	27	167.1			129.1		
		F. avenaceum			*Epicoccum*		
Fungicide	9	149.9	2.1	ns	1019.0	3.8	**
Residual	27	72.2			266.7		
		Cladosporium			*Alternaria*		
Fungicide	9	565.7	1.6	ns	54.4	0.9	ns
Residual	27	352.5			61.3		

FIFE

		F. culmorum			*F. nivale*		
Fungicide	9	11.9	0.9	ns	1076.4	2.7	***
Residual	27	12.5			·151.5		
		F. avenaceum			*Epicoccum*		
Fungicide	9	143.3	0.8	ns	369.1	1.5	ns
Residual	27	183.5			253.7		
		Cladosporium			*Alternaria*		
Fungicide	9	808.3	1.8	ns	39.0	1.0	ns
Residual	27	457.4			37.7		

APPENDICES VI-VII. Effects of ear inoculation with different fungal species on grain development of different cereal species and cultivars, 1987-1988

Abbreviations

df	degrees of freedom
ms	mean squares
vr	variance ratio
sig	significance
ns	non-significant
*	significant at probability level of P = 0.05
**	significant at probability level of P = 0.01
***	significant at probability level of P = 0.001

APPENDIX VI. Glasshouse experiment-1987. Effects of cultivar, fungal species and date of inoculation.

SOURCE OF VARIATION	df	ms	vr.	sig.
(a) GRAIN NUMBER				
Rep	3	969		
Cultivar	4	23529	135.0	***
Fungi	5	8556	1.7	ns
CV*FU	20	14251	0.6	ns
Residual	87	79384		
Date	2	80429	20.0	***
DA*CV	8	9334	2.3	*
DA*FU	10	5713	1.4	ns
DA*CV*FU	40	3229	0.8	ns
Residual	180	4037		
(b) GRAIN WEIGHT/ 5 EARS				
Rep	3	222.4		
Cultivar	4	1487.9	97.9	***
Fungi	5	55.1	3.6	**
CV*FU	20	8.2	0.5	ns
Residual	87	15.2		
Date	2	196.4	36.5	***
DA*CV	8	23.4	4.5	***
DA*FU	10	6.5	1.2	ns
DA*CV*FU	40	5.9	1.1	ns
Residual	180	5.4		
(c) 1000 GRAIN WEIGHT				
Rep	3	7231.5		
Cultivar	4	76798.8	134.7	***
Fungi	5	941.2	1.7	ns
CV*FU	20	342.2	0.6	ns
Residual	87	570.0		
Date	2	3217.2	19.9	***
DA*CV	8	373.3	2.3	*
DA*FU	10	228.5	1.4	ns
DA*CV*FU	40	131.7	0.8	ns
Residual	180	161.5		

APPENDIX VII. Glasshouse experiment-1988. Effects of cultivar, fungal species and date of inoculation.

SOURCE OF VARIATION	df	ms	vr.	sig.
(a) GRAIN NUMBER				
Cultivar	5	2080581	272.7	***
Fungi	7	21631	2.8	**
CV*FU	35	7030	0.9	ns
Residual	144	7630		
Date	2	247352	168.6	***
DA*CV	10	23543	16.1	***
DA*FU	14	4112	2.8	***
DA*CV*FU	70	1656	1.1	ns
Residual	288	1467		
(b) GRAIN WEIGHT/5 EARS				
Cultivar	5	1960.2	313.1	***
Fungi	7	159.2	25.4	***
CV*FU	35	16.2	2.6	***
Residual	144	6.3		
Date	2	813.5	379.0	***
DA*CV	10	62.8	29.3	***
DA*FU	14	11.7	5.5	***
DA*CV*FU	70	4.0	1.8	***
Residual	288	2.1		
(c) 1000 GRAIN WEIGHT				
Cultivar	5	58.5	0.6	ns
Fungi	7	2399.8	23.2	***
CV*FU	35	124.8	1.2	ns
Residual	144	103.7		
Date	2	4850.9	86.3	***
DA*CV	10	299.8	5.3	***
DA*FU	14	172.0	3.1	***
DA*CV*FU	70	97.2	1.7	***
Residual	288	56.2		

APPENDIX VIII. Glasshouse experiment-1989. Effects of cultivar, date of inoculation, inoculum treatment with *T. roseum* and fungal species.

SOURCE OF VARIATION	df	ms	vr.	sig.
(a) GRAIN NUMBER				
Cultivar	1	222.3	0.1	ns
Residual	2	3728.6		
Date	2	8531.0	3.6	ns
DA*CV	2	1045.8	0.4	ns
Residual	4	2377.9		
Inoculum Type	2	335.0	0.9	ns
CV*INO	2	687.3	1.9	ns
DA*INO	4	157.0	0.4	ns
CV*DA*INO	4	168.7	0.5	ns
Residual	12	367.5		
Fungi	7	147.0	0.5	ns
CV*FU	7	96.0	0.3	ns
INO*FU	14	117.0	0.4	ns
DA*FU	14	269.1	0.9	ns
CV*INO*FU	14	86.8	0.3	ns
CV*DA*FU	14	427.7	1.4	ns
DA*INO*FU	28	500.9	1.7	*
Residual	154	297.9		
(b) GRAIN WEIGHT/ 5 EARS				
Cultivar	1	1.2	0.1	ns
Residual	2	14.7		
Date	2	14.0	2.3	ns
DA*CV	2	9.1	1.5	ns
Residual	4	6.2		
Inoculum Type	2	1.6	1.4	ns
CV*INO	2	1.7	1.5	ns
DA*INO	4	3.5	3.0	ns
CV*DA*INO	4	0.6	0.5	ns
Residual	12	1.2		
Fungi	7	10.1	12.8	***
CV*FU	7	0.3	0.3	ns
INO*FU	14	1.2	1.5	ns
DA*FU	14	1.2	1.6	ns
CV*INO*FU	14	0.6	0.7	ns
CV*DA*FU	14	1.5	1.9	*
DA*INO*FU	28	1.5	2.0	**
Residual	154	0.8		
(c) 1000 GRAIN WEIGHT				
Cultivar	1	16.5	0.03	ns
Residual	2	520.5		
Date	2	46.4	0.2	ns
DA*CV	2	812.2	3.8	ns
Residual	4	211.3		
Inoculum Type	2	130.9	2.7	ns
CV*INO	2	7.4	0.2	ns
DA*INO	4	134.7	2.8	ns
CV*DA*INO	4	18.4	0.4	ns
Residual	12	47.6		
Fungi	7	784.5	28.4	***
CV*FU	7	40.3	1.5	ns
INO*FU	14	65.8	2.4	**
DA*FU	14	48.0	1.7	ns
CV*INO*FU	14	22.1	0.8	ns
CV*DA*FU	14	46.0	1.7	ns
DA*INO*FU	28	31.9	1.2	ns
Residual	154	27.6		

APPENDICES IX-XII. Effects of ear inoculation with different fungal species on seed performance of different cereal species and cultivars, 1987-1988

Abbreviations

df	degrees of freedom
ms	mean squares
vr	variance ratio
sig	significance
ns	non-significant
*	significant at probability level of P = 0.05
**	significant at probability level of P = 0.01
***	significant at probability level of P = 0.001

APPENDICES XIII-XVII. Effects of seed and soil inoculation with different fungal species on seed performance of different cereal species and cultivars, 1987-1989

Abbreviations

df degrees of freedom

ms mean squares

vr variance ratio

sig significance

ns non-significant

*   significant at probability level of P = 0.05

**   significant at probability level of P = 0.01

*** significant at probability level of P = 0.001

APPENDIX IX. Glasshouse experiment-1987. Effects of cultivars, fungal species and date of inoculation.

SOURCE OF VARIATION	df	ms	vr.	sig.
(a) SEED HEALTH TEST				
Replicates	3	383		
Seed. treat.	1	26281	152.7	***
Cultivar	4	692	4.0	**
Fungi	5	71239	414.0	***
Time	2	31864	185.2	***
Ste*Cul	4	910	5.3	***
Ste*Fun	5	3930	22.8	***
Cul*Fun	20	558	3.2	***
Ste*Tim	2			
Cul*Tim	8	414	2.4	*
Fun*Tim	10	1641	9.5	***
Ste*Cul*Fun	20	304	1.77	*
Ste*Cul*Tim	8	662	3.8	***
Ste*Fun*Tim	10	194	1.1	ns
Cul*Tim*Tim	40	306	1.8	**
Residual	577	172		
(b) % UNGERMINATED SEED				
Replicates	3	48		
Cultivar	4	1601	105.9	***
Fungi	5	2881	604.3	***
Time	2	2803	391.6	***
Cul*Fun	20	394	28.8	***
Cul*Tim	8	445	21.8	***
Fun*Tim	10	468	32.4	***
Cul*Fn*Tim	40	138	6.5	***
Residual	267	29		
(c) % ABNORMAL SEEDLINGS				
Replicates	3	40		
		786		
Cultivar	4	9087	31.0	***
Fungi	5	4347	357.9	***
Time	2	326	171.2	***
Cul*Fun	20	697	12.8	***
Cul*Tim	8	268	27.4	***
Fun*Tim	10	220	10.6	***
Cul*Fn*Tim	40	25	8.6	***
Residual	267			
(d) SHOOT LENGTH				
Replicates	3	1.1		
Cultivar	4	36.6	71.6	***
Fungi	5	283.0	554.6	***
Time	2	68.9	135.9	***
Cul*Fun	20	6.0	11.8	***
Cul*Tim	8	7.7	15.2	***
Fun*Tim	10	3.6	7.0	***
Cul*Fn*Tim	40	3.0	5.6	***
Residual	267	0.5		
(e) ROOT LENGTH				
Replicates	3	2.7		
Cultivar	4	4.7	9.6	***
Fungi	5	199.7	411.8	***
Time	2	43.6	89.8	***
Cul*Fun	20	3.4	7.0	***
Cul*Tim	8	2.3	4.8	***
Fun*Tim	10	1.6	3.3	***
Cul*Fn*Tim	40	1.6	3.3	***
Residual	267	0.5		

APPENDIX X. Glasshouse experiment-1988. Effects of cultivars, fungal species and date of inoculation.

SOURCE OF VARIATION	df	ms	vr.	sig.
(a) SEED HEALTH TEST				
Replicates	3	2477		
Fungi	7	101767	92.2	***
Time	2	8603	7.8	***
Cultivar	5	2742	2.5	*
Seed treat.	1	71726	65.0	***
Fun*Tim	14	7374	6.7	***
Fun*Cul	35	3082	2.8	***
Tim*Cul	10	3665	3.3	***
Fun*Ste	7	3347	3.0	**
Tim*Ste	2	19232	17.4	***
Cul*Ste	5	4932	4.5	***
Fun*Tim*Cul	70	2196	2.0	***
Fun*Tim*Ste	14	2275	2.1	*
Fun*Cul*Ste	35	2059	1.9	**
Tim*Cul*Ste	10	2768	2.5	**
Residual	931	1104		
(b) % UNGERMINATED SEED				
Replicates	3	117		
Fungi	7	22730	489.0	***
Time	2	9788	210.6	***
Cultivar	5	654	14.1	***
Fun*Tim	14	1549	33.3	***
Fun*Cul	35	290	6.2	***
Tim*Cul	10	162	3.5	***
Fun*Tim*Cul	70	140	3.0	***
Residual	429	46		
(c) % ABNORMAL SEEDLINGS				
Replicates	3			
Fungi	7	10993	203.3	***
Time	2	7119	131.6	***
Cultivar	5	2140	36.6	***
Fun*Tim	14	1290	23.8	***
Fun*Cul	35	522	9.6	***
Tim*Cul	10	181	3.4	***
Fun*Tim*Cul	70	297	5.5	***
Residual	429	54		
(d) PLUMULE LENGTH				
Replicates	3	0.1		
Fungi	7	321.7	857.7	***
Time	2	50.1	133.7	***
Cultivar	5	25.1	66.9	***
Fun*Tim	14	4.2	11.3	***
Fun*Cul	35	7.7	20.4	***
Tim*Cul	10	1.3	3.6	***
Fun*Tim*Cul	70	1.0	2.7	***
Residual	429	0.4		

APPENDIX XI. Glasshouse experiment-1989. Effects of fungal species and date of inoculation:- Barley cv. Camargue.

SOURCE OF VARIATION	df	ms	vr.	sig.
(a) SEED HEALTH TEST				
Replicates	2	149		
Seed treat.	1	4366	28.1	***
Time	2	56510	364.0	***
Inoculum treat.	2	3120	20.1	***
Fungi	7	40374	260.0	***
Ste*Tim	2	360	2.3	ns
Ste*Ino	2	228	1.5	ns
Tim*Ino	4	682	4.4	**
Ste*Fun	7	443	2.9	**
Tim*Fun	14	2571	16.6	***
Ino*Fun	14	1522	9.8	***
Ste*Tim*Ino	4	76	0.5	ns
Ste*Tim*Fun	14	358	2.3	**
Ste*Ino*Fun	14	468	3.0	***
Tim*Ino*Fun	28	1780	11.5	***
Residual	314	155		
(b) % DISEASE SEVERITY INDEX IN SHOOTS				
Replicates	3	101		
Time	2	22091	368.2	***
Inoculum	2	2346	39.1	***
Fungi	7	3640	60.7	***
Tim*Ino	4	907	15.1	***
Tin*Fun	14	1317	21.9	***
Ino*Fun	14	248	4.1	**
Tim*Ino*Fun	28	554	9.2	***
Residual	213	60		
(c) % DISEASE SEVERITY INDEX IN ROOTS				
Replicates	3	6		
Time	2	23820	625.9	***
Inoculum	2	3129	82.2	***
Fungi	7	5040	132.5	***
Tim*Ino	4	542	14.2	***
Tin*Fun	14	968	25.5	***
Ino*Fun	14	809	21.3	***
Tim*Ino*Fun	28	693	18.2	***
Residual	213	38		
(d) SHOOT LENGTH				
Replicates	3	5.5		
Time	2	454.8	308.2	***
Inoculum	2	22.7	15.4	***
Fungi	7	237.2	160.7	***
Tim*Ino	4	17.0	11.5	***
Tin*Fun	14	14.0	9.5	***
Ino*Fun	14	11.1	7.6	***
Tim*Ino*Fun	28	8.4	5.7	***
Residual	213	1.5		
(e) ROOT LENGTH				
Replicates	3	1.8		
Time	2	37.3	47.3	***
Inoculum	2	75.9	96.2	***
Fungi	7	88.1	111.7	***
Tim*Ino	4	27.7	35.1	***
Tin*Fun	14	9.4	12.0	***
Ino*Fun	14	3.4	4.3	***
Tim*Ino*Fun	28	8.4	10.6	***
Residual	213	0.8		

APPENDIX XII. Glasshouse experiment-1989. Effects of fungal species and date of inoculation:- Barley cv. Sherpa.

SOURCE OF VARIATION	df	ms	vr.	sig.
(a) SEED HEALTH TEST				
Replicates	2	136		
Seed treat.	1	890	7.0	**
Time	2	16533	132.0	***
Inoculum treat.	2	4158	33.2	***
Fungi	7	49680	396.6	***
Ste*Tim	2	2859	22.8	***
Ste*Ino	2	511	4.1	*
Tim*Ino	4	314	2.5	*
Ste*Fun	7	662	5.3	***
Tim*Fun	14	2383	19.0	***
Ino*Fun	14	1023	8.2	***
Ste*Tim*Ino	4	502	4.0	**
Ste*Tim*Fun	14	402	3.2	***
Ste*Ino*Fun	14	105	0.8	ns
Tim*Ino*Fun	28	459	3.7	***
Residual	314	125		
(b) % DISEASE SEVERITY INDEX IN SHOOTS				
Replicates	3	91		
Time	2	4683	191.7	***
Inoculum	2	4255	92.4	***
Fungi	7	26060	565.7	***
Tim*Ino	4	268	5.8	***
Tin*Fun	14	1104	24.0	***
Ino*Fun	14	1014	22.0	***
Tim*Ino*Fun	28	498	10.8	***
Residual	213	46		
(c) % DISEASE SEVERITY INDEX IN ROOTS				
Replicates	3	72		
Time	2	8333	136.2	***
Inoculum	2	3465	56.6	***
Fungi	7	25343	414.1	***
Tim*Ino	4	837	13.7	***
Tin*Fun	14	816	13.3	***
Ino*Fun	14	690	11.3	***
Tim*Ino*Fun	28	480	7.8	***
Residual	213	61		
(d) SHOOT LENGTH				
Replicates	3	1.3		
Time	2	405.7	411.3	***
Inoculum	2	42.5	43.1	***
Fungi	7	341.3	346.0	***
Tim*Ino	4	24.5	24.9	***
Tin*Fun	14	17.4	17.7	***
Ino*Fun	14	14.3	14.5	***
Tim*Ino*Fun	28	4.7	4.8	***
Residual	213	1.0		
(e) ROOT LENGTH				
Replicates	3	0.5		
Time	2	160.8	277.5	***
Inoculum	2	61.1	105.4	***
Fungi	7	168.0	290.0	***
Tim*Ino	4	38.4	66.3	***
Tin*Fun	14	5.4	9.4	***
Ino*Fun	14	5.7	9.9	***
Tim*Ino*Fun	28	7.9	13.7	***
Residual	213	0.6		

APPENDIX XIII. Glasshouse experiment-1987. Effects of seed inoculation with different *Fusarium* species and *Trichothecium roseum* treatment on seedling emergence:- Barley cv. Golden Promise.

SOURCE OF VARIATION	df	ms	vr.	sig.
Replicates	3	298		
Fungi	5	8299	32.8	***
T. roseum treat.	8	9315	36.9	***
Fun * Treat.	40	1330	5.3	***
Residual	159	253		

APPENDIX XIV. Glasshouse experiment-1987. Effects of seed and soil inoculation with different *Fusarium* species and *Trichothecium roseum* treatment on seedling emergence:- Barley cv. Golden Promise.

SOURCE OF VARIATION	df	ms	vr.	sig.
Fungi	5	4307	19.7	***
Residual	18	219		
T. roseum treat.	3	4519	10.1	***
Substrate	1	9776	39.1	***
Fun * treat.	15	1109	4.4	***
Fun * Subst.	5	684	2.7	*
Treat. * Subst.	3	6167	24.6	***
Fun * Treat. Subst.	15	1116	4.5	***
Residual	126	250		

APPENDIX XVI. Effects of seed inoculation with different inoculum rates of *F. culmorum* and *Trichothecium roseum* on seedling germination of wheat cv. Dollar.

SOURCE OF VARIATION	df	ms	vr.	sig.
(a) % UNGERMINATED SEEDS				
Replicates	3	9		
Inoculum rate.	7	1887	47	***
Residuals	21	40		
(a) % ABNORMAL SEEDLINGS				
Replicates	3	73		
Inoculum rate	7	4862	63	***
Residuals	21	77		

APPENDIX XV. Effects of seed inoculation with *Trichothecium roseum* treatment on seedling performance of different cultivars and species of cereal crops.

SOURCE OF VARIATION	df	ms	vr.	sig.
(a) % UNGERMINATED SEEDS				
Replicates	3	256		
T. roseum treat.	1	7223	78.8	***
Cultivars	6	135	1.5	ns
Treat * Cult.	6	202	2.2	ns
Residuals	39	92		
(a) % ABNORMAL SEEDLINGS				
Replicates	3	123		
T. roseum treat.	1	2224	183	***
Cultivars	6	1019	8.4	***
Treat * Cult.	6	898	7.4	***
Residuals	39	122		

APPENDIX XVII. Effects of seed inoculation with different *Fusarium* and other fungal species on seedling germination of wheat cv. Dollar.

SOURCE OF VARIATION	df	ms	vr.	sig.
(a) % UNGERMINATED SEEDS				
Replicates	3	190		
Fusarium	5	1340	4.7	***
Fungi	5	4088	14.2	***
Fus * Fun	25	565	2.0	**
Residuals	21105	287		
(a) % ABNORMAL SEEDLINGS				
Replicates	3	151		
Fusarium	5	68	1.9	ns
Fungi	5	29.6	0.8	ns
Fus * Fun	25	35.3	1.0	ns
Residuals	105	35.5		