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BRASSICAS: CONTROL OF CLUBROOT (*PLASMODIOPHORA BRASSICAE*) USING INTEGRATED APPLICATION OF BORON AND SURFACTANT

BRASSICAS: CONTROL OF CLUBROOT (*PLASMODIOPHORA BRASSICAE*) USING INTEGRATED APPLICATION OF BORON AND SURFACTANT

by G R DIXON[1], R. KENNEDY[2], L BAIRD[1] and D M KENYON[1]

EXPERIMENTATION UNDERTAKEN IN SCOTLAND IN 1995 & 1996 AND ENGLAND IN 1995 WITH THE OBJECTIVE OF DETERMINING THE EFFICACY OF BORON, AGRAL AND MIXTURES OF BORON AND AGRAL FOR THE INTEGRATED CONTROL OF *PLASMODIOPHORA BRASSICAE* -- THE CAUSAL AGENT OF CLUBROOT DISEASE OF BRASSICACEAE

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PRACTICAL SECTION FOR GROWERS

Clubroot, caused by the soil-borne fungus *Plasmodiophora brassicae* is the major source of uncontrolled crop loss for *Brassica* growers. There are no effective fungicides of practical significance or resistant cultivars of any agronomic merit. Consequently growers must manipulate their husbandry operations in order to favour the host and disadvantage the pathogen. This is traditionally achieved by raising soil pH to 6.5 - 7.0 and ensuring efficient drainage.

Research by SAC and HRI independently over several years, has highlighted improvements in the control of clubroot achieved through applications of boron and the surfactant Agral™ at planting. The introduction of targetted applications of nutrients at planting of *Brassica* grown in modules ('Starter Fertiliser') offers an opportunity for integrating methods of clubroot limitation with crop fertiliser systems. As a result a series of field scale experiments was jointly established in Scotland and England over two years to determine the extent of control which might be achieved using solutions containing boron and Agral™.

Results have indicated advantages to growers of adding boron at 15ppm and Agral™ at planting, resulting in reduced disease severity and/or increased yields. As is common with all forms of control for clubroot these advantages are variable and depend upon interactions with weather, site and the erratic distribution of the fungus within fields. Additional research, outwith the HDC contract but nonetheless reported here, also highlighted levels of disease control which can be achieved where growers use calcium nitrate rather than ammonium nitrate fertiliser.

Currently, growers of *Brassica* crops must achieve control of this increasingly severe disease problem through careful manipulation of fertiliser inputs supported by the treatments described in this Report. The additional costs of such measures are minimal especially when compared with the total crop loss which this fungus causes.

Both Dr Kennedy (HRI) and Professor Dixon (SAC/University of Strathclyde) clearly cautioned the HDC Field Vegetable Panel when this Project was first discussed, December 1994, that significant further refinements aiming to determine application rates, efficacy of combinations and timings would be required should growers wish to see this research provide greater practical support to growers faced with the devastating consequences of clubroot infestation.

SCIENTIFIC SUMMARY

Experiments are reported which studied the efficacy of boron and the proprietary wetter 'Agral' both singly and in combination for the control of *Plasmodiophora brassicae*, the causal agent of clubroot disease of *Brassicae*. These trials extended over five sites in Scotland and England and over two seasons (1995 and 1996). This was a collaborative research programme between SAC and HRI.

Results reinforced the previous independent studies which had indicated both in controlled experiments and commercial practice that there is a beneficial reduction in the damage caused by *P. brassicae* (clubroot) where applications of boron and Agral are included in the husbandry protocol. Control was shown to be enhanced where combined treatments are used. Indeed the combination of boron, Agral, addition of calcium, enhancement of pH beyond 6.5 and manipulation of the form of nitrogenous fertiliser away from ammonical towards nitrate compounds further reduced the impact of clubroot and benefited the crops being produced.

All the results emphasised that these forms of integrated husbandry based controls are significantly influenced by both the aerial and edaphic environments. The level of control achieved is reliant upon a complex matrix of interrelated factors. This means that the absolute levels of control achieved by a single factor in any one season will vary significantly from the overall mean achieved over a period of years. Consequently the larger the combination of factors which the grower can manipulate and control as part of the husbandry package then the greater the probability of achieving satisfactory disease reduction becomes.

One major result was apparent from these studies, in that applications of 'high' concentrations of boron (>15 ppm) over the entire trials series failed to cause significant phytotoxicity and the extensive soil analyses have demonstrated conclusively that there is a very limited retention of the element around the rhizosphere after about 14 days from application. This result would indicate that an even higher dose rate could be advocated to growers (say 20 ppm) which might further enhance the chances of achieving increased clubroot control.

The original research specification supplied by Dr Kennedy and Professor Dixon to the Horticultural Development Council Field Vegetables Panel called for trials of several rates and combinations of treatment integrated with experiments under controlled conditions. This approach would have enabled the research to proceed on a logical scientific basis rather than the current *ad hoc* system.

Nonetheless, the current work has achieved substantial progress since it is apparent that growers should as a matter of routine include enhanced applications of boron and Agral in their husbandry systems.

FURTHER INVESTIGATIONS

1. Investigate the use of increased doses of boron and Agral at several sites over several season

2. Determine the impact of pH on the efficacy of the boron and Agral treatments

3. Integrate the use of calcium nitrate into this experimental series such that the efficacy of non - ammonical fertilisers in reducing the impact of clubroot can be determined. Again this should study the interaction of rates x doses x sites x seasons.

4. Research each of the above with other treatments which are of current commercial interest, for example, use of calcium cyanamide (Perlka™) which has recently become available to British growers at an economic price.

5. Determine an integrated package which will enable more specific control systems to be used to advantage by prolonging their efficacy in the face of the development of chemically tolerant races of *P. brassicae.*

6. Investigate the opportunities for the use of biological control agents and their admixture with organically composted derivatives, again in combination with those systems already investigated for the current Report.

INTRODUCTION

Clubroot, caused by the soil-borne fungus *Plasmodiophora brassicae* (Woronin) is one of the most difficult plant pathogens to control in cultivated cruciferous crops world-wide. The pathogen forms characteristic galls or clubs on the roots of the plant reducing its yield potential. Severe infection often leads to plant wilting and death resulting in total crop failure.

Traditional control measures have included improving drainage, liming the soil to raise the pH and rotating brassica crops with non-cruciferous crops. In the UK clubroot has often been controlled in the field by treatment with mercurous chloride (Calomel). This chemical is, however, highly persistent and toxic to mammals and its approval for use has been revoked by regulatory authorities. At present there is no specific fungicidal chemical which can be used to control the disease effectively and alternative control treatments are urgently required.

Research over the past 15 years using controlled environment, glasshouse and field experimentation has clearly demonstrated that applications of boron in excess of 15 ppm will retard the development of galling symptoms caused by *Plasmodiophora brassicae* Wor. in members of the Brassicaceae. The mode of action of this effect is via the retardation of morphogenesis of the primary stages of development of *P. brassicae* in the host root hairs and in inhibiting symptom expression in the secondary cortical cell stage.

A summary of this research was published by Dixon (1996, *Acta Horticulturae*). This basic research has been supported by Borax Consolidated Ltd., 170 Priestley Road, Guildford, Surrey, GU2 5RQ (Company colleague: Dr Martin Phillips) for several years.

The late Dr F. Humpherson-Jones identified that the proprietary wetting agent Agral (alkyl phenyl ethylene oxide) when applied to *Brassica* transplants substantially reduced clubroot disease in field grown crops (*Annals of Applied Biology, 122 (3) 457-465; 1993*). Applications of alkyl phenyl ethylene oxide have been shown to control successfully disease development and to increase yield of cabbage in trials at HRI-Wellesbourne.

Consequently, combining effective treatments such as the modification of soil pH and application of Agral and boron were investigated at HRI-Wellesbourne and SAC-Auchincruive. This approach was advocated to The Horticultural Development Council over several years as suitable for collaborative experimentation.

Previously, over several seasons empirical field studies of boron and Agral both separately and as mixtures have been accomplished with the assistance of Messrs East of Scotland Growers, Prestonhall House, Prestonhall Industrial Estate, Cupar, Fife, KY15 4RD. Results from this work indicated the efficacy of these materials for the control of clubroot in commercial crops of calabrese. Before this treatment could be recommended to growers on a wider scale, however, there was a need for thorough testing using replicated field trials at several sites as widely dispersed as possible in the UK. To this purpose Dr R Kennedy (Horticulture Research International, Wellesbourne) and Professor G R Dixon (SAC and University of Strathclyde) have undertaken the research which is reported here.

This current Report to The Horticultural Development Council (HDC) (Contract: FV 177) summarises results obtained by collaboration between HRI-Wellesbourne and SAC-Auchincruive in which field experiments were conducted over the period 1995-1996 at sites in Angus, Ayrshire, Cornwall, Fife, and Warwickshire. Also included are data obtained in glasshouse experimentation which indicate the need to manipulate pH as part of an integrated control system.

Borax Consolidated Ltd generously provided support for some of this field research. Consequently, this Report is also provided to Borax Consolidated Ltd., Guildford, Surrey and to East of Scotland Growers who provided the land and facilities for the experiments at Redford, Angus and at Crail, Fife.

MATERIALS AND METHODS

Treatments

Field trials comparing the effect of solutions containing either 0.2% Agral or 15 ppm boron alone or in combination applied directly to the root zone at transplanting were carried out using land naturally infested with *P. brassicae* (clubroot). These were compared with untreated naturally infested plots.

Crop husbandry schedules for each site are given in Tables 1 - 7. Each treatment had six replicate plots (arranged as six blocks with one replicate of each treatment per block). Replicates were randomised within blocks at the time of transplanting.

The trials were replicated on three adjacent areas of infected land which had been amended to different soil pH levels at HRI Wellesbourne. Three pH areas were situated according to a soil sample taken in the field on the 9 May 1995.

The trials at SAC-Auchincruive were repeated over the 1995 and 1996 seasons using land heavily and uniformally infested by *P. brassicae* at pH = 6.5.

Trials were repeated at two commercial sites in Cornwall (1995) and at Redford, Angus (1995) and Crail, Fife (1996). In these trials no attempts, beyond those included in standard local husbandry procedures, were made to control pH.

Assessment of clubroot infection

Clubroot was assessed on the entire root system after the plant had been removed from the soil and any loose soil removed from the root system. The presence of clubroot (severity of clubroot galls) was assessed a scale of 1 (no clubroot present) to 5 (heavily clubbed roots) in the HRI trials and on 0 (no clubroot present) to 3 (heavily clubbed roots) in the SAC trials.

Application of chemicals

Agral was applied at 0.2% in 70 ml to the planting hole prior to transplanting. Boron was applied in 100 ml to the planting hole prior to transplanting at a concentration of 15 ppm. The concentration of Boron was achieved by mixing 72.12 mg of Solubor in 1 litre of water. This amount at this concentration gave 3-4 ppm Boron around the root system when sampled.

Assessment of boron concentration

Approximately 100g of soil was taken from the root zone surrounding the plant using an auger. The soil was dried and milled prior to determination of soil boron (using standard advisory service procedures).

Assessment of plant yield

At final harvest the total head weight including leaves and the weight of harvestable spears was taken for each plant in each replicate plot.

Statistical treatment of results

Harvest results at each site were analysed by ANOVA. Weighted means were used in the analysis of gall scores and ANOVA was used on log-transformed means of total head weights where appropriate by HRI-Wellesbourne; SAC-Auchincruive used analyses of recorded data without further transformation treatments. Analyses used Genstat 5 (Rothamsted Research Station).

CROP PRODUCTION SCHEDULES

Table 1 Husbandry procedures - SAC-Redford, Angus 1995

Land ploughed and cultivated as per local practice
Fertiliser applied as 1:1:1 at 100 units ha^{-1}
Starter fertiliser applied at transplanting as 11:40:3.5 at 1.25ml per plant
Top dressing of nitrogen at 172 units ha^{-1}
Herbicide and insecticide: at pre-planting Treflan at 1.1 l ha^{-1} product (half normal rate)
at post-planting Butisan S at 1.5 l ha^{-1} product
at post-planting Sherriff at 25 kg ha^{-1} product
at post-planting 3 applications of Decis at 300 ml ha^{-1}
at post-planting 2 applications of Aphox at 420 g ha^{-1}
Trial area marked out on 27 June
Treatments applied with a Cooper Pegler 3 sprayer; each plot contained 5 rows of 20 plants
Trial area and surrounding crop planted on 28 June with *B oleracea* var *botrytis* cv Shogun (calabrese)
Trial inspected 4 July
Trial assessed for vigour and phytotoxicity damage on 13 July
Control of Spear Rot with Cuprokyt at 5 kg ha^{-1}
During crop life 3 applications of irrigation at 6.25 cm ha^{-1} per application
Plots harvested on 12 September when 40 heads were taken from the centre 3 rows of each plot and weighed; roots lifted and scored for symptoms using the scale: 0 = nil symptoms; 3 = more than 50% root with galling symptoms.

Table 2 Husbandry procedures - SAC-Auchincruive, Ayrshire 1995

Seed of *B oleracea* var *capitata* cv Castello (summer cabbage) sown into modules containing peat based compost supplemented with Birlane, for cabbage root fly control (5kg product per 640 litres of compost) under heated glass on 9 May; transferred to unheated glass on 30 May
Land treated with farmyard manure and ploughed over winter
Secondary cultivations in March and April
Fertiliser as 2:1:1 applied 11-12 June at 200 units ha^{-1} and transplanting beds prepared
Plots marked out as 5 rows each to contain 20 plants; treatments applied using a Cooper Pegler 3 sprayer
Whole area sprayed with Grammoxone to provide stale seed bed
Plots planted by machine (Super Prefer 5 rows) on 20 June with immediate post-planting applications of herbicide Dacthal-Ramrod at 5 kg product ha^{-1} and 9 l product ha^{-1}, respectively, and Draza moluscicide 15 kg product ha^{-1}; all plots were netted against vermin (pigeons, rabbits, hares, deer) and irrigated with 6.25 cm ha^{-1}
Trial scored for vigour and phytotoxicity damage 14 July
Overall spray with Decis 300 ml product ha^{-1} 28 July
Plots were harvested on 2 October, cutting and trimming 50 heads to marketing standards and weighing; clubroot symptoms scored on 0-3 scale where 0 = nil symptoms and 3 = more than 50% of the root with galling symptoms.

Table 3 Husbandry Procedures SAC-Auchincruive 1996

Procedures used were essentially similar to those used in 1995 with the exception of dates:
Land ploughed over winter and treated with 60 t/ha farmyard manure
Seed sown under heated glass 6 May
Plants transferred to unheated glass 28 May
Field cultivations and fertiliser (2:1:1 at 750 kg/ha) 14 May
Planting and herbicide applications 25 June
Spray for control of aphid and caterpillar 8 August
Plots harvested, assessed for disease development and heads weighed 30 September

Table 4 Husbandry Procedures SAC-Crail, Fife, 1996

Soil series Raised Beach
Soil texture Medium loam
Previous cropping Calabrese at two crops per year for the past 5 years
Cultivar Marathon
Spacing 40cm
Planting date 18 July
Fertiliser 750 kg/ha 12:15:20 applied 12 July plus 1.5 t/ha lime plus 250 kg/ha calcium ammonium nitrate applied on 12 and 16 July
Other inputs: Butisan S 1.5 l/ha product applied 27 July; Hallmark 150 ml/ha product, Aphox 280 g/ha product, Ambush C 150 ml/ha product, Yaltox 1 g/m product at planting, Manganese 2.0 l/ha 19 August, Fubol 58 1.5 kg/ha product 22 August
Irrigation 7.5 cm throughout the growing season
Treatment date (Agral plus Boron) 18 July
Crop harvest date 4 October.

Table 5 Husbandry Procedures HRI-Wellesbourne 1995

Each plot was grown at a spacing of 33 x 33 cm.
Crop areas were established within each pH area of the quarantine field according to pH samples taken on the 9/10 May 1995.
Sowing date 15 May 1995
Transplant date 15 June 1995
Plot Size Each replicate plot measured approximately 6 m x 1 m with six replicate plots for each treatment. Each pH area was divided into six blocks of approximately 6 x
4 m in area. Each of the four treatments was sited randomly in each block. A total area of approximately 12m x 12 m was used in each of the three pH areas.
Cultivar cv. Shogun
Worked ground and nitrogen applied @ 190 kg/ha June 14
Yaltox applied @ 0.4 g/plant June 15
Albrass applied @ 9.0 l/ha June 16
Dacthal applied @ 6.0 kg/ha June 16
DSM applied @ 500 ml/ha to sprouts June 21
Hostaquick applied @ 840 ml/ha July 3
Dimethoate applied @ 1.0 l/ha July 16
N applied @ 100 kg/ha to calabrese July 18
Ambush C applied @ 250 ml/ha to sprouts July 31
Dipterex applied @ 1.75 kg/ha plus Agral August 3
Decis applied @ 300 ml/ha August 17
Field harvested September 27

Table 6 Husbandry Procedures HRI-Camborne

Each plot was grown at a spacing of 69 x 69 cm.
Trial area was established within the field according to the results of a field wide sampling of pH conditions.
Sowing date 22 May 1995
Transplant date 11 July 1995
Plot Size Each replicate plot was approximately 9.6 m x 2 m with six replicate plots for each treatment. The trial site will be divided into six blocks of approximately 19.2 x 8 m in area. Each of the four treatments will be sited randomly in each block. The total trial covered an area of approximately 19.2m x 24m.
Cultivar cv. Belot

Table 7 Husbandry Procedures HRI- Scorrier

Crop plan Each plot was grown at a spacing of 56 x 76 cm.
Siting Trial area was established within the field according to the results of a field wide sampling of pH conditions.
Sowing date 22 May 1995
Transplant date 10 July 1995
Plot Size Each replicate plot was approximately 7.2 m x 2.2 m there was six replicate plots for each treatment (see Figure 5). The trial site was divided into six blocks of approximately 7.2 x 8.8 m in area. Each of the four treatments will be sited randomly in each block. The total trial covered an area of approximately 14.4m x 26.4m.
Cultivar cv. Elsoms 1641 (Prior)

RESULTS AND DISCUSSION

Results for the entire trials series for five sites and two seasons are given in Tables 8 - 29.

The application of boron raised soil concentrations at both the Redford and Auchincruive sites both immediately and at 14 days after application (Tables 8, 9, 11 and 12). These effects were more apparent at Auchincruive than at Redford. At Redford the increase immediately after application was 7% where boron alone was applied and 9% where the mixture of boron and Agral was used. The increases at Auchincruive were far greater being 160% for the boron alone and 174% for the boron + Agral plots. It seems that Agral may make boron more available in soil. The samples taken at 14 days showed that application of boron at Redford increased the root zone availability by 5% and by 13.7% where the mixture of boron+Agral was used. Again at Auchincruive boron in samples taken 14 days after application was increased by 27% in the boron alone and by 34.7% in the boron + Agral plots. It is apparent that adding the wetter makes for greater availability of boron on both soil types. The soils at Redford are derived from Old Red Sandstone and hence have a high sand content while those at Auchincruive are from the Bargour Series and are classed as sandy clay loams. This could be very significant in terms of promoting the use of boron for the control of clubroot (*Plasmodiophora brassicae)*.

There was a complete failure for the development of clubroot symptoms in the trial at Redford, Angus in 1995 (Table 10). This is despite the very heavy level of disease which was experienced on this site in 1994, which encouraged the Farm Manager to advocate this land area for the trials in the current year. Such an effect can only be attributed to the very hot and dry season which was experienced in 1995 which did not permit the organism to infect and develop in the susceptible calabrese crop grown on the site. None of the treatments had any statistically significant effect upon crop yield and there was no evidence of phytotoxicity derived from any of the treatments.

In the trials at Auchincruive application of boron increased head yield from cabbage by 9% while Agral increase head yield by 7%; the combined application of boron + Agral had no significant effect on yield (Table 13). Boron reduced clubroot symptoms by 7% and Agral applications reduced clubroot symptoms by 8%. The combination of boron+Agral was associated with an increase in clubroot symptom development.

The levels of clubroot symptom reduction obtained by the use of boron at planting vary with season but under favourable circumstances can reach 50%. It is apparent that in the very hot dry season experienced in 1995 control levels were reduced substantially. Similarly in the Redford experiment high temperature inhibited symptom development almost entirely.

In the 1996 trials at SAC-Auchincruive applications of boron again raised the soil boron content around the plant roots immediately after treatment but this effect was less marked than in 1995 (Tables 14, 15, 16). There were no significant differences obtained between treatment in this trial (Table 17).

In parallel with these HDC funded studies others were made of the effect of applications of nitrogen in the ammonium and nitrate forms and in combination with boron. Experiments were

made both in the field and in the glasshouse. Results clearly demonstrated the efficacy of using nitrogen in the form of calcium nitrate, especially when supplemented with boron for the reduction of severity of clubroot symptoms as compared with the use of ammonium nitrate or calcium ammonium nitrate (Table 18).
NB:- THIS DATA IS INCLUDED FOR EXPLANATION ONLY AND IS NOT FOR FURTHER USE BY HDC

The 1996 trial at Crail, Fife, also raised the soil boron content in line with the treatments used, but these effects were only transitory. Results were not significantly different between treatments but Agral was associated with better yields and lower clubroot incidence compared with boron. There was a very high soil boron status to begin with which possibly reflects continued use by the East of Scotland Growers of this treatment over several seasons.

The trials made by HRI at Wellesbourne (Tables 22 and 23) produced significantly lower clubroot infection and higher mean head weights of Calabrese cv. Shogun in treatments where Agral alone or in combination with boron had been applied in comparison with either untreated plots or those given only boron in trials at HRI Wellesbourne (Table 23). The effect was more pronounced in infected plots which had been adjusted to pH 6.8. However in other plots, with a mean soil pH of 7.5, there was little difference between treatments and little or no clubroot infection was observed (Table 23). There was an increase in total head weight where Agral alone or in combination with boron had been applied in comparison to uninfected untreated controls grown in a separate area which was not infested with clubroot (results not shown). The difference was considerably higher when these treatments were compared to untreated infected controls. Application of Solubor to the soil had little effect on extractable boron in samples removed from the root zone in comparison to treatments where boron had not been applied (Table 22). Application of Agral or boron had no effect on soil pH (Table 22). Trials were established at two commercial sites in Cornwall on cauliflower in which the same treatments were tested (Tables 24-29).

At the first commercial trial site near Camborne cv. Belot was treated with either Agral or boron alone or in combination. These treatments were compared to an untreated control. There was no modifications of soil pH incorporated within the trial at the Camborne site.

The second site was located in east Cornwall near St Agnes on cauliflower cv Prior. The second trial was sited on ground which had not received any pH modification however the remainder of the site was amended with sand and an additional replicate of each treatment was located on this pH amended ground.

At the first commercial trial site in Cornwall (Kehelland, Camborne), significantly lower clubroot scores were recorded in treatments where Agral had been applied alone in comparison to untreated plots and those treatments where boron had been applied alone or in combination with Agral (Table 25). Mean total head weights were higher where Agral and boron had been applied in combination in comparison to other treatments though this was not significant. Agral applied alone was more effective in controlling clubroot than the other treatments tested. The barely significant differences in clubroot score where Agral was applied alone suggests that these differences may have resulted in a generally poor relationship between the level of clubroot symptoms and cauliflower total head weight (Table 25). There

were no differences between treatments in the amount of extractable boron in samples removed from the root zone (Table 24). Application of Agral or boron had no effect on soil pH (Table 24) and soil pH levels were generally very favourable for clubroot development.

The trial was repeated (as at Camborne) using cauliflower cultivar Prior. at the second commercial trial site in Cornwall (Trewellard, St Agnes) (Tables 26-29). Significantly lower clubroot scores were recorded in treatments where either Agral or Boron had been applied alone or in combination in comparison to untreated plots (Tables 28 and 29). The effect was more marked where treatments of Agral and boron had been applied to cauliflowers planted in ground which had been pH modified using sand (Table 29). Treatments where Agral had been applied alone had significantly lower clubroot than treatments where only boron had been applied.

The harvest of this trial was delayed by several months due to low temperatures during February and March 1996. Consequently there were no significant differences between treatments in the total head weight of cauliflowers. The results were less marked than would have been expected given the level of clubroot development which was observed. There was generally less clubroot development where Agral had been applied. The effect of Agral on clubroot score and total head weight was more marked where Agral had been applied to soil and the pH had been raised (Table 29). No statistics could be carried out on this part of the trial as it was unreplicated. There were no differences between treatments in the amount of extractable boron in samples removed from the root zone (Tables 26 and 27). Application of Agral or boron had no effect on soil pH (Tables 26 and 27) and soil pH levels were generally very favourable for clubroot development.

TABLES OF RESULTS

1. REDFORD, ANGUS TRIAL 1995

Table 8 Soil fertility analysis taken immediately following the application of treatments

Nutrient	Treatment			
	Control	Boron	Agral	Boron+Agral
pH (water)	6.8	6.8	6.8	6.8
Available P mg l^{-1}	223	229	218	224
Available K mg l^{-1}	228	296	260	260
Magnesium mg l^{-1}	384	488	528	400
Salinity mS cm^{-1}	0.68	0.77	0.78	0.76
Calcium mgl^{-1}	3040	3440	3280	3200
Nitrogen mgl^{-1}	177	220	205	207
Boron mg kg^{-1}	1.82	1.95	1.91	1.99

Table 9 Soil fertility analyses taken 14 days after treatment application

Nutrient	Treatment and plot number						
	Untreated Controls						
	3	6	8	9	11	20	mean
pH (water)	6.7	7.1	6.7	6.8	7.2	6.8	6.9
Available P mg l^{-1}	167	156	175	170	137	188	166
Available K mg l^{-1}	224	148	256	212	134	244	203
Magnesium mg l^{-1}	384	400	472	344	340	392	389
Salinity mS cm^{-1}	0.92	0.45	1.10	0.93	0.48	0.86	0.79
Calcium mg l^{-1}	3408	2896	3264	3056	3024	2848	3083
Nitrogen mg l^{-1}	223	96	285	248	104	194	192
Boron mg kg^{-1}	1.74	1.60	1.70	1.68	1.63	1.74	1.68
	Boron treatment						
	4	7	12	13	19	21	mean
pH (water)	6.7	7.2	6.8	6.8	7.0	6.9	6.9
Available P mg l^{-1}	186	141	179	181	154	158	167
Available K mg l^{-1}	240	144	228	252	212	212	215
Magnesium mg l^{-1}	368	376	320	352	392	408	369
Salinity mS cm^{-1}	0.84	0.57	0.82	0.97	0.75	0.78	0.78
Calcium mg l^{-1}	3184	2960	2720	3240	3328	3520	3159
Nitrogen mg l^{-1}	216	126	207	259	173	198	197
Boron mg kg^{-1}	1.77	1.70	1.58	1.95	1.77	1.78	1.76

	Agral treatment						
	1	10	14	16	17	23	mean
pH (water)	6.9	7.1	7.1	6.7	6.8	7.1	7.0
Available P mg l^{-1}	188	146	147	172	184	158	166
Available K mg l^{-1}	200	144	168	232	240	184	195
Magnesium mg l^{-1}	392	376	340	400	360	384	375
Salinity mS cm^{-1}	0.68	0.50	0.52	0.74	0.92	0.68	0.67
Calcium mg l^{-1}	3312	3280	3152	2944	3168	3248	3190
Nitrogen mg l^{-1}	164	108	108	182	245	172	163
Boron mg kg^{-1}	1.76	1.60	1.78	1.74	1.79	1.43	1.68

	Boron + Agral treatment						
	2	5	15	18	22	24	mean
pH (water)	7.0	6.9	7.1	7.1	7.1	6.9	7.0
Available P mg l^{-1}	155	157	151	158	170	166	160
Available K mg l^{-1}	220	204	164	180	220	252	207
Magnesium mg l^{-1}	384	400	336	376	368	368	372
Salinity mS cm^{-1}	0.76	0.82	0.60	0.58	0.72	0.84	0.72
Calcium mg l^{-1}	3168	3072	3344	3360	3424	3600	3328
Nitrogen mg l^{-1}	172	213	129	133	170	210	171
Boron mg kg^{-1}	2.09	1.96	1.91	1.80	1.89	1.78	1.91

Table 10 Yield of calabrese spears and assessment of clubroot symptoms

Treatment	Spear weight (g)	Clubroot assessment*
Untreated	120.99	0.07
Boron	110.59	0.11
Agral	110.13	0.07
Boron + Agral	114.36	0.09
SED	9.96	0.05
Significance	ns	ns

* clubroot symptoms assessed on the scale 0=nil symptoms; 3=<50% root affected

2. AUCHINCRUIVE, AYRSHIRE TRIALS 1995

Table 11 Soil fertility analysis taken immediately after the application of treatments

Nutrient	Treatment			
	Control	Boron	Agral	Boron+Agral
pH (water)	6.2	6.1	6.1	6.1
Available P mg l^{-1}	0.4	34	36	39
Available K mg l^{-1}	408	396	432	464
Magnesium mg l^{-1}	112	108	128	120
Salinity mS cm^{-1}	0.72	0.60	0.74	0.74
Calcium mg l^{-1}	1648	1648	1680	1744
Nitrogen mg l^{-1}	190	198	195	189
Boron mg kg^{-1}	0.69	1.11	0.73	1.20

Table 12 Soil fertility analysis taken 14 days after treatment application

Nutrient	Treatment and plot number						
	Control						
	1	11	17	19	22	24	Mean
pH (water)	6.2	6.1	6.1	6.3	6.1	6.1	6.2
Available P mg l^{-1}	31	26	42	20	31	24	29
Available K mg l^{-1}	300	376	416	346	440	448	388
Magnesium mg l^{-1}	88	112	96	100	120	104	103
Salinity mS cm^{-1}	0.44	0.52	0.64	0.48	0.83	0.66	0.60
Calcium mg l^{-1}	1544	1592	1488	1664	1600	1504	1565
Nitrogen mg l^{-1}	117	113	197	129	238	180	162
Boron mg l^{-1}	0.70	0.72	0.72	0.78	0.64	0.77	0.72
	Boron						
	4	6	13	15	20	21	Mean
pH (water)	6.1	6.1	6.1	6.2	6.2	6.2	6.2
Available P mg l^{-1}	37	32	32	23	21	21	28
Available K mg l^{-1}	328	464	448	308	384	388	387
Magnesium mg l^{-1}	96	120	112	104	120	120	112
Salinity mS cm^{-1}	0.61	0.75	0.54	0.51	0.73	0.59	0.62
Calcium mg l^{-1}	1592	1640	1816	1584	1792	1664	1681
Nitrogen mg l^{-1}	176	186	121	116	184	120	151
Boron mg kg^{-1}	0.96	0.85	0.90	1.06	0.95	0.79	0.92
	Agral						
	3	5	8	10	16	23	Mean
pH (water)	6.2	6.1	6.1	6.2	6.2	6.2	6.2
Available P mg l^{-1}	30	34	34	26	25	19	28
Available K mg l^{-1}	300	398	332	448	356	368	367
Magnesium mg l^{-1}	96	112	96	112	112	120	108
Salinity mS cm^{-1}	0.53	0.54	0.55	0.66	0.51	0.53	0.55
Calcium mg l^{-1}	1608	1632	1488	1600	1624	1728	1613
Nitrogen mg l^{-1}	126	127	132	175	111	136	135
Boron mg kg^{-1}	0.71	0.75	0.70	0.64	0.63	0.68	0.69
	Boron + Agral						
	2	7	9	12	14	18	Mean
pH (water)	6.1	6.1	6.2	6.1	6.2	6.2	602
Available P mg l-1	37	27	31	23	26	26	28
Available K mg l-1	346	372	440	336	376	342	369
Magnesium mg l-1	96	112	112	104	112	104	107
Salinity mS cm-1	0.59	0.48	0.64	0.59	0.43	0.51	0.54
Calcium mg l-1	1600	1696	1728	1560	1680	1556	1637
Nitrogen mg l-1	166	114	170	137	94	113	132
Boron mg kg-1	0.78	0.99	1.09	1.02	0.96	0.99	0.97

Table 13 Cabbage head weight and clubroot symptoms assessment

Treatment	Head weight (g)	clubroot assessment
Control	242.20	2.13
Boron	264.18	1.98
Agral	258.19	1.95
Boron+Agral	243.78	2.19
SED	20.3	0.095
Significance	**	**

3.) AUCHINCRUIVE, AYRSHIRE TRIALS 1996

Table 14 Soil fertility analyses taken prior to the application of treatments

Determination	Experimental Treatments			
	Untreated	Boron	Agral	Boron + Agral
pH	6.0	6.0	6.0	5.9
Extractable phosphorus mg/l	12.1	11.2	11.4	17.0
Extractable potassium mg/l	323	312	323	331
Extractable magnesium mg/l	123	133	121	120
Extractable calcium mg/l	1530	1440	1490	1500
Extractable sodium mg/l	24.5	24.3	24.5	23.5
Extractable boron mg/l	0.88	0.87	0.84	0.90
conductivity CF	2.45	2.42	2.61	2.93

Table 15 Soil fertility analyses taken 7 days after planting

Determination	Treatments			
	Untreated plots	Boron treated plots	Agral treated plots	Boron + Agral treated plots
pH	6.1	6.2	6.1	6.1
Boron mg/l	0.86	0.98	0.88	1.11

Table 16 Soil fertility analyses taken 14 days after planting

Determination	Treatments			
	Untreated plots	Boron treated plots	Agral treated plots	Boron + Agral treated plots
pH	5.9	6.0	6.0	6.0
Boron mg/l	0.94	0.96	0.90	0.92

Table 17 Cabbage yield and assessments of clubroot symptoms

Treatment	Yield (head weight g)	Clubroot symptom*
Untreated plots	224.6	1.8
Boron treated plots	237.8	1.8
Agral treated plots	218.0	2.1
Boron + Agral treated plots	210.2	2.1
SED	30.18	0.22
Significance *P*	ns	ns

Clubroot symptoms assessed on 0 - 3 scale where 0 = nil symptoms; 3 = > 50 % of the root galled, Boron applied at 15 ppm, Agral applied at 2 % solution

Table 18 Interaction of Calcium and Boron nutrition on the intensity of clubroot symptoms and yield of the host (NON HDC FUNDED RESEARCH)

THIS TABLE IS INCLUDED FOR INFORMATION ONLY

Treatment	Field Experiment		Glasshouse Experiment	
	Cabbage yield g per head	Clubroot symptoms*	Chinese cabbage yield g per head	Clubroot symptoms*
Ammonium nitrate 200 kg/ha	401	88.5	55.0	97.9
Calcium nitrate 200 kg/ha	507	75.9	63.9	64.6
Calcium nitrate 300 kg/ha	610	63.1	79.4	57.1
Calcium ammonium nitrate 200 kg/ha	436	86.7	67.4	93.2
Calcium nitrate + Boron 200 kg /ha	482	76.0	84.1	30.5
Calcium nitrate + Boron 300 kg / ha	566	67.1	104.2	50.1
LSD (*P*)	81.8	9.81	16.19	13.65

* Clubroot symptoms expressed as Disease Index on 0 - 100 % scale of ascending disease

4). CRAIL, FIFE TRIAL 1996

Table 19 Soil fertility analyses taken at planting

Determination	Treatments			
	Untreated	Boron	Agral	Boron + Agral
pH	6.9	7.0	6.9	7.0
Extractable Boron mg/l	3.50	4.01	3.82	3.79

Table 20 Soil fertility analyses taken 14 days after planting

Determination	Treatments			
	Untreated	Boron	Agral	Boron + Agral
pH	7.0	7.1	6.9	7.1
Boron mg/l	3.44	3.40	2.99	3.23

Table 21 Calabrese yield and clubroot symptoms

Treatment	Calabrese spear weight g	Clubroot symptoms*
Untreated plots	220.4	2.08
Boron treated plots	175.0	2.38
Agral treated plots	209.2	2.13
Boron + Agral treated plots	187.0	2.43
SED	30.44	0.285
Significance *P*	ns	ns

Clubroot symptoms assessed on 0 - 3 scale where 0 = nil symptoms; 3 = > 50 % of the root galled, Boron applied at 15 ppm, Agral applied at 2 % solution

5). HRI-WELLESBOURNE TRIAL 1995

Table 22 Soil pH and Boron content (ug/ml) at Wellesbourne(infected land) after planting

Treatment						
pH	6.0		6.8		7.5	
	pH	Boron	pH	Boron	pH	Boron
Agral	6.09	nm	6.80	nm	7.45	nm
Boron	6.15	0.33	6.86	0.38	7.58	0.28
Agral + Boron	6.04	0.32	6.95	0.36	7.48	0.31
Infected Untreated	6.05	0.30	6.93	0.20	7.54	0.20

nm - not measured

Table 23 Calabrese head weight (g) and clubroot score at Wellesbourne(infected land)

Treatment						
pH	6.0		6.8		7.5	
	Head Weight (g)	Clubroot Assessment	Head Weight	Clubroot Assessment	Head Weight	Clubroot Assessment
Agral	484 (6.16)	2.87	536 (6.24)	2.77	606 (6.40)	1.00
Boron	332 (5.79)	3.99	307 (5.51)	4.05	653 (6.48)	1.03
Agral + Boron	479 (6.17)	3.05	552 (6.29)	2.36	611 (6.41)	1.04
Infected Untreated	367 (5.89)	3.60	304 (5.62)	3.93	654 (6.47)	1.01
SED (75 d.f.)	(0.129)	0.295	(0.129)	0.295	(0.129)	0.295

6). HRI TRIAL CAMBORNE, CORNWALL 1995

Table 24 Soil pH and Boron content (ug/ml) at Camborne after planting

Treatment	pH	Boron content (ug/ml)
Agral	5.64	nm
Boron	5.68	0.27
Agral + Boron	5.69	0.26
Untreated	5.49	0.28

nm - not measured

Table 25 Cauliflower head weight (g) and clubroot score at Camborne

Treatment	Head Weight (g)	Clubroot Score
Agral	1093 (7.29)	2.93
Boron	839 (7.20)	3.42
Agral + Boron	1142 (7.08)	3.54
Untreated	959 (7.05)	3.79
SED	(0.154)	0.353

7). HRI TRIAL SCORRIER, CORNWALL 1995

Table 26 Soil pH and Boron content at Scorrier after planting (unamended soil)

Treatment	pH	Boron Content (ug/ml)
Agral	6.02	nm
Boron	5.90	0.32
Agral + Boron	5.89	0.34
Untreated	5.84	0.33

nm - not measured

Table 27 Soil pH and Boron content at Scorrier after planting (amended soil)

Treatment	pH	Boron Content (ug/ml)
Agral	6.28	nm
Boron	5.93	0.32
Agral + Boron	6.22	0.34
Untreated	6.30	0.33

nm - not measured

Table 28 Cauliflower head weight (g) and clubroot score at Scorrier (unamended soil)

Treatment	Head Weight (g)	Clubroot Score
Agral	973 (7.08)	3.06
Boron	1010 (7.10)	3.83
Agral + Boron	919 (7.19)	3.20
Untreated	948 (7.12)	4.35
SED	(0.154)	0.353

APPENDIX 1

METEOROLOGICAL RECORDS - MONTHLY AVERAGES 1995

	Temperature oC			Rainfall (mm)
	Maximum	Minimum	Soil (30cm)	
Scottish Crop Research Institute, Dundee, for the Redford site				
July	20.0	10.7	15.7	0.9
August	22.1	11.5	16.7	0.3
SAC-Auchincruive				
July	20.4	11.9	15.0	3.0
August	21.3	12.0	16.2	0.8
September	16.9	9.4	14.3	2.5

APPENDIX 2

METEOROLOGICAL RECORDS - MONTHLY AVERAGES 1996

	Temperature ^{o}C		Rainfall mm
	Maximum	Minimum	
SAC -Auchincruive			
May	12.4	4.0	42.0
June	16.5	8.9	58.2
July	17.3	10.5	49.4
August	18.7	11.6	48.1
September	17.1	9.0	27.8
October	13.7	8.3	146.7
Mylnefield, Dundee			
June	16.9	8.8	52.5
July	18.5	10.4	56.5
August	18.3	10.2	66.7
September	15.8	8.5	67.0
October	12.5	6.3	62.8
November	8.2	2.3	57.2