12 Agriolimacidae, Arionidae and Milacidae as Pests in West European Cereals

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Introduction

Small-grain cereals (mainly wheat (*Triticum aestivum* Linnaeus) and barley (*Hordeum vulgare* Linnaeus)) (Gramineae) are the most important arable crops grown in western Europe. For example, in the European Union in 1993/94, production of wheat and barley (74 and 43 million t, respectively) was substantially greater than that of maize (*Zea mays* Linnaeus) (Gramineae) (29 million t) (Renshaw, 1994). In the UK in 1994 and 1996 (Table 12.1), wheat alone occupied 38–41% of the total area of arable land and barley occupied 23–26%. Smaller areas of oats (*Avena sativa* Linnaeus) (Gramineae), rye (*Secale cereale* Linnaeus) (Gramineae) and triticale (the allohexaploid between diploid rye and tetraploid wheat) are also grown. Wheat, barley, oats and rye are grown for human consumption (wheat as bread, pasta, breakfast cereals, etc., barley mainly for malting, oats mainly for breakfast cereals and rye mainly for bread) and animal feed. Triticale is used mainly for animal feed.

Wheat is undoubtedly the most important crop damaged by gastropods in western Europe, in terms of the area at risk and the area requiring treatment with molluscicides. For example, 27% of the wheat area in the UK was treated with molluscicides in 1994, representing 61% of the total area treated in that year (Table 12.1). Barley, oats, rye and triticale are also susceptible to damage. Surveys in Great Britain in the 1960s and 1970s (Strickland, 1965; Hunter, 1969; Stephenson and Bardner, 1977) indicated that 0.2–2.2% of the wheat crop was lost to gastropods. Port and Port (1986) pointed out that more recent estimates are not available for the extent of losses in cereal crops, but the increase of molluscicide use from the 1960s to 1982 clearly demonstrated that farmer perception of gastropods in these crops had increased considerably. Subsequent surveys indicate a 67-fold increase in molluscicide usage in

Table 12.1. Total areas of cereals and other arable crops grown and areas treated with molluscicides in Great Britain, 1994 (from Garthwaite *et al.*, 1995) and 1996 (from Thomas *et al.*, 1997).

Crop	Total area (ha) grown	Area (ha) treated with molluscicides	Area treated as % of total crop area	Area treated as % of total area treated
Wheat (*Triticum aestivum* Linnaeus) (Gramineae)				
1994	1,802,190	485,950	27.0	60.5
1996	1,967,270	266,290	13.5	56.8
Spring barley (*Hordeum vulgare* Linnaeus) (Gramineae)				
1994	450,600	280	0.1	0.1
1996	491,210	2,730	0.6	0.6
Winter barley (*Hordeum vulgare* Linnaeus) (Gramineae)				
1994	620,130	73,150	11.0	9.1
1996	740,880	34,180	4.6	7.3
Oats (*Avena sativa* Linnaeus) (Gramineae)				
1994	105,950	7,840	7.4	1.0
1996	93,450	1,200	1.2	0.2
Rye (*Secale cereale* Linnaeus) (Gramineae)				
1994	7,350	0	0	0
1996	8,220	0	0	0
Triticale (*Secale cereale* Linnaeus × *Triticum aestivum* Linnaeus) (Gramineae)				
1994	5,660	1,220	21.5	0.2
1996	7,100	0	0	0
Oilseed rape (*Brassica napus* Linnaeus var. *oleifera* Linnaeus) (Brassicaceae)				
1994	403,470	120,830	29.9	15.0
1996	355,850	72,390	20.3	15.5
Other arable				
1994	634,840	86,960	13.7	10.8
1996	610,270	83,700	13.7	17.9
Set-aside				
1994	725,930	25,870	3.6	3.2
1996	506,220	7,940	1.6	1.7
All arable crops				
1994	4,756,120	802,100	16.9	–
1996	4,780,470	468,430	9.8	–

Great Britain between the early 1970s and 1994/95 (Garthwaite and Thomas, 1996). Autumn-sown cereals are at greater risk than spring-sown cereals, so the trend in recent decades towards autumn sowing has contributed greatly to the increase in the use of molluscicides in cereal crops. Other agronomic changes have also contributed, as described in this chapter. However, it is important to note that molluscicide use on arable crops (mainly cereals) over the period from 1980 to 1995 (Garthwaite and Thomas, 1996) and into 1996 (Thomas *et al.*, 1997) shows considerable year-to-year fluctuations with no general upward trend.

Gastropods are most important during the crop-establishment phase with damage to seeds and seedlings (Moens, 1980, 1989; Martin and Kelly, 1986; Port and Port, 1986; Glen, 1989; Gratwick, 1992). Gastropods kill wheat seeds by eating the embryo, with destruction of part or all of the endosperm. The extent of damage to individual wheat seeds varies greatly, but, because the gastropods always destroy critical meristem tissues, the seed is always killed, irrespective of the amount of the tissue consumed. Gastropods also kill young seedlings after germination by destroying critical tissues, such as the meristem at the base of the shoot (Gair *et al.*, 1987; Gratwick, 1992). These animals may also graze on and destroy the leaves of seedlings after emergence, but, once the plants have reached the tillering stage, this leaf damage is generally not considered to be of any great importance. In wet summers, however, gastropods can damage the flag leaves just below the developing wheat seed heads (Kemp and Newell, 1987; Gratwick, 1992), which may lead to a reduction in yield (Kemp and Newell, 1987).

Barley and oats suffer similar damage to wheat, but these crops are considered to be at lesser risk. This is because gastropods prefer wheat (Duthoit, 1964), partly due to the absence of the natural seed coating found in barley and oats and also because of agronomic practices: barley and oats are seldom grown immediately after oilseed rape (*Brassica napus* Linnaeus var. *oleifera* Linnaeus) (Brassicaceae) in the rotation (Glen, 1989), barley is normally drilled earlier in the autumn than winter wheat (Port and Port, 1986) and barley is not usually grown on the clay soils where gastropods are most troublesome (Brown, 1955). The role of oilseed rape is explained below.

Surveys of arable farmers and crop consultants in England and Wales in the mid-1980s amply demonstrated industry concern about gastropod damage to cereals (Glen, 1989). In one questionnaire, farmers and crop consultants belonging to the Long Ashton Members' Association (LAMA) were invited to identify the pest causing them greatest concern in a range of crops. The replies showed (Fig. 12.1) that gastropods were the pests causing most concern to wheat growers and these came second only to aphids as a source of anxiety among producers of barley crops.

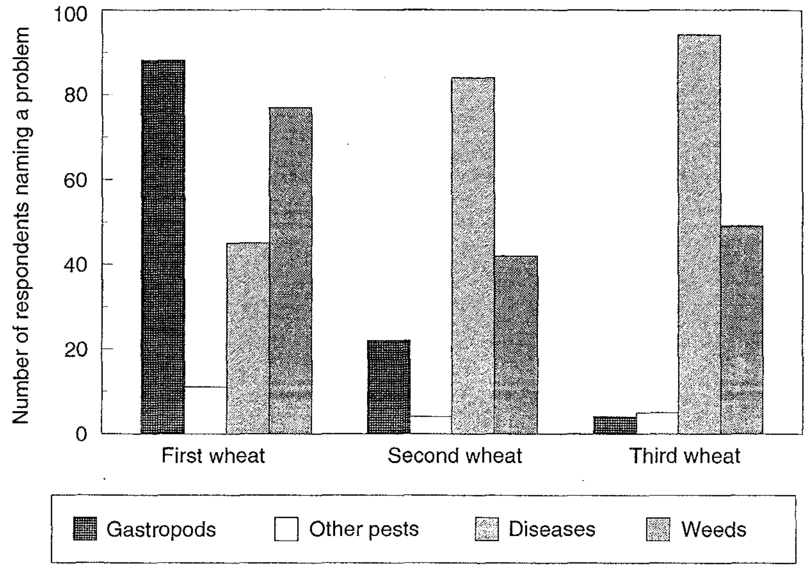


Fig. 12.1. Perceptions by farmers and consultants in England and Wales of the importance of gastropods, together with other pests, diseases and weeds, as problems in first, second and third wheat (*Triticum aestivum* Linnaeus) (Gramineae) crops after oilseed rape (*Brassica napus* Linnaeus var. *oleifera* Linnaeus) (Brassicaceae) (from Glen, 1989).

Gastropod Species Responsible for Damage

The agriolimacid *Deroceras reticulatum* (Müller) is considered to be the most common gastropod pest species in cereal crops and cereal-dominated rotations in western Europe (Runham and Hunter, 1970; Glen and Wiltshire, 1988; Moens, 1989). However, *D. reticulatum* usually occurs together with other gastropod species with the slug body form, particularly members of the families Arionidae and Milacidae (Brown, 1955; Gould, 1961; Duthoit, 1964; Glen *et al.*, 1984, 1989, 1992b; Kemp and Newell, 1987; Glen and Wiltshire, 1988; Hommay *et al.*, 1991; Hommay, 1995). Shelled gastropods (snails) are relatively rare in cereal fields in western Europe and are not recognized as pests in these environments, in contrast to southern Australia (see Baker, Chapter 6, this volume). Duthoit (1964) showed that all species of gastropod that she found in UK cereal fields were capable of damaging cereal seeds and seedlings in the laboratory. While *D. reticulatum* consumed more seeds of wheat than barley, *Arion hortensis* agg. (Arionidae) ate about equal numbers of each and *Tandonia budapestensis* (Hazay) (Milacidae) ate more barley than wheat seeds. All species tended to eat both the embryo and the endosperm of wheat seeds, but only the embryo of barley seeds. Oat seeds were virtually undamaged by the gastropods under these conditions. When given the choice of seeds or seedlings, *D. reticulatum*, *Arion ater* (Linnaeus) and *Arion fasciatus* agg. all caused equal damage to both, whereas *A. hortensis* agg. and *T. budapestensis* were more likely to damage seeds than seedlings. On balance, Duthoit (1964) concluded that *D. reticulatum* and *A. ater* were potentially the most damaging species present in cereal crops, mainly because of their greater appetite compared with other species, but also because of their feeding preferences. Given that *D. reticulatum* is much more prevalent than *A. ater* in arable fields with cereal-dominated crop rotations (Glen and Wiltshire, 1988), the former species is generally considered to be the most important pest species. However, it should be noted that, if gastropod biomass is more important than numbers in determining the severity of damage, as suggested by Glen *et al.* (1989), other gastropod species may be of more importance than indicated by their abundance. For example, although Glen *et al.* (1989) found that *D. reticulatum* (96 m^{-2}) was about six times as abundant as *Arion distinctus* (Mabille) and *Arion subfuscus* (Draparnaud) (15 m^{-2} and 13 m^{-2}, respectively) in a wheat seed-bed, the biomass of all three species was similar (1.3–1.5 g m^{-2}).

Factors Affecting Gastropod Damage to Cereals

Damage to cereals depends on gastropod abundance, feeding rate per individual and the vulnerability of the crop to damage. Each of these factors is considered below.

Gastropod abundance in cereal crops

The difficulty of estimating gastropod abundance in arable fields has greatly limited our understanding of their pest status in cereals. Gastropod slugs live in the soil as well as on the soil surface and methods of extracting these animals from soil are generally considered slow and laborious. The soil-flooding process devised by South (1964) for grassland and modified by Hunter (1968) for arable crops, has been refined at Long Ashton and used extensively to study populations in the upper 100 mm of soil in cereal fields (Glen *et al.*, 1984, 1988, 1989, 1990, 1992a,b, 1994a,b, 1996; Glen and Wiltshire, 1986; Wiltshire and Glen, 1989; Wilson *et al.*, 1994a; Bohan *et al.*, 1997, 2000a,b). It is widely recognized that gastropod populations in cereals are greatly influenced by agricultural practices. Furthermore, their populations in cereal crops exhibit considerable fluctuation both within and between years, even when agricultural practices do not appreciably change. These gastropods are strongly dependent on moisture for feeding, reproduction and survival, so that their numbers and distribution are greatly influenced by soil moisture, as well as by temperature. However, populations in cereal crops have been observed to decline in certain years when soil moisture and temperature were apparently favourable (Glen *et al.*, 1988, 1996), when there were no obvious changes in crop husbandry and when populations remained high or increased at other sites. This pattern suggests that natural enemies may be responsible for marked variation in population size, but our lack of understanding of the system precludes the prediction of abundance so vital to the management of the pests.

Spatial pattern in cereal fields

Hunter (1966) found that *D. reticulatum*, *A. hortensis* agg. and *T. budapestensis* moved to greater depth in arable soil during a dry period, as they also did in cold weather in winter. In a winter wheat crop, Glen *et al.* (1984, 1992b) found that *D. reticulatum*, *Arion intermedius* Normand and *Arion silvaticus* Lohmander were virtually absent from the upper 10 cm of soil during the dry summers of 1983 and 1984, but numbers rapidly recovered when the soil became moist again in autumn. This suggests that these gastropods survived dry conditions by moving deep into the soil, possibly using cracks that opened in the clay soil as it dried out. The ability of gastropod slugs to move to sources of moisture at depth in clay and silt soils may, in part, explain why they are more troublesome pests of cereals grown on such soils, but a higher moisture-retention capacity in such soils also contributes to better survival. In shallow soils and those of a sandy nature and thus of low moisture retention, gastropod slugs are unable to survive dry weather conditions in this way.

Gastropods are known to have underdispersed (aggregated) dispersion patterns and this has been confirmed for species resident in agricultural fields (South, 1965; Hunter, 1966; Airey, 1984). Recent studies of the distribution patterns of *D. reticulatum* and *A. intermedius* in a cereal field (Bohan *et al.*, 1997, 2000a,b; Shirley *et al.*, 1998) have revealed spatial dynamics not previously appreciated. Hot spots of abundance of *D. reticulatum* were found distributed at random throughout the cereal field (Bohan *et al.*, 2000b) in a spatial pattern that was consistent with predictions from a model of the movement and survival of individuals of this species (Shirley *et al.*, 1998). However, *A. intermedius* was found in a stable patch, within an area about 40 m in diameter (Bohan *et al.*, 2000b). This difference in distribution patterns is consistent with the contrasting biology of these two species, *D. reticulatum* being more surface-active, breeding at any time of year and reaching maturity faster than the less active, strictly annual, autumn-breeding *A. intermedius*. The action of natural enemies can be expected to operate in a non-random way but their contribution to the spatial dynamics of species like *D. reticulatum* and *A. intermedius* is only beginning to be understood, as explained below. The available evidence suggests that gastropod individuals move only relatively small net distances in cereal fields (South, 1965; Pinder, 1969; Fleming, 1989; Glen *et al.*, 1991) and populations in cereals are thought not to be greatly influenced by migration from adjacent field margins, such as wild-flower strips (Frank, 1998). This conclusion is supported by observations that gastropod damage is typically more severe in the middle of cereal fields than at the edges (Gould, 1961), which is the opposite of the pattern expected if migration from field margins were important.

Effects of cultural practices on gastropod populations

CROP ROTATION. Gould (1961) showed, in surveys of crops in East Anglia, that winter-wheat crops following in rotation such dense, leafy crops as pea (*Pisum sativum* Linnaeus) (Fabaceae) were at greater risk from gastropod damage than wheat following either fallow or crops such as potato (*Solanum tuberosum* Linnaeus) (Solanaceae), which leave relatively more bare soil between vegetated rows. The incidence of gastropod damage in wheat has increased greatly since Gould's survey because of a large expansion since the 1970s in the area planted to oilseed rape and its prevalence in rotation with wheat (Stephenson and Bardner, 1977; Martin and Kelly, 1986; Port and Port, 1986). In a survey in 1986/87 (Glen, 1989), farmers and consultants in LAMA were invited to name one pest, disease and weed (only one of each) that they had most encountered in first, second and third wheat crops after a break crop of oilseed rape. If they had not encountered a pest, disease or weed problem in these crops, then no reply was given. It is clear (Fig. 12.1) from the respondents that gastropods were not only considered to be the most important pest invertebrate group, but also the most pressing crop-protection issue in the first wheat crops to follow rape in the rotation. Gastropods were considered important compared with other pest invertebrates in second and third wheat crops after rape, but invertebrates were considered to be relatively unimportant in comparison with disease and weed problems in these crops (Fig. 12.1).

Further evidence of the greater risk of gastropod damage to winter-wheat crops following rape, compared with those following cereals, was provided by a survey throughout the UK from 1987 to 1990 (Glen *et al.*, 1993). This increased risk has been attributed to a higher abundance of gastropods, but the evidence for this was not conclusive. It is important to note here that populations do not inevitably increase within oilseed-rape crops: Glen *et al.* (1996), for example, reported no increase in gastropod populations in an oilseed-rape crop that followed 3 years of cereals that had supported high gastropod numbers.

CROP-RESIDUE DISPOSAL. In the 1970s and 1980s in the UK, it was common practice for farmers to dispose of unwanted cereal straw by burning *in situ* (Prew and Lord, 1988). Studies during the period 1982–1988 showed that gastropod populations tended to be greater in plots where straw or stubble was not burned than where straw was burned (Glen *et al.*, 1984, 1988). Thus, straw burning tended to depress gastropod populations, although gastropods did not appear to be affected directly by heat, but rather by removal of food and shelter (Glen *et al.*, 1988). However, atmospheric pollution problems associated with straw burning led initially to restrictions in straw burning in the 1980s (Prew and Lord, 1988), followed by a complete ban on the practice in the UK in 1993.

Farmers currently dispose of cereal straw either by baling and transport from the fields, thus leaving only the stubble behind, or they chop and spread the straw on the soil surface for later incorporation. On a clay soil in Oxfordshire, no consistent difference was found between gastropod populations residing in plots subjected to these two practices (Glen *et al.*, 1984, 1988). However, at this site, severe reduction in seedling numbers due to gastropod damage and the resulting poor yield of wheat crops (Christian *et al.*, 1999) probably restricted the amount of chopped straw returned and thus may not have been typical of normal farm-practice conditions. In a more recent long-term study, from 1988 onwards, gastropod populations have been consistently greater where straw was chopped, spread on the soil surface and subsequently incorporated by cultivation than where the straw was baled and removed (Glen *et al.*, 1994b; Kendall *et al.*, 1995; Symondson *et al.*, 1996).

Incorporation of crop residues improves soil structure and returns nutrients to the soil for recycling. For these reasons, in farming systems designed to combine profitable farming with environment protection, incorporation is the preferred method of disposing of crop residues (Jordan and Hutcheon, 1996), despite the resulting increase in gastropod numbers, at least in the initial years where such systems are adopted (Glen *et al.*, 1996).

CULTIVATION. It is generally accepted that gastropod populations are favoured by conservation tillage relative to traditional cultivation, which reduces numbers (see reviews by Martin and Kelly, 1986; Port and Port, 1986). Hunter (1967) observed that gastropod numbers were reduced by cultivation of an arable loam soil and considered much of this to have been caused by mechanical injury to the gastropods. Exposure of gastropods to high radiant temperatures and predation on the soil surface could also contribute to reductions in numbers following cultivation (Martin and Kelly, 1986). Ploughing and subsequent cultivations to produce a seed-bed for drilling winter cereals often result in substantial reductions in gastropod populations (Glen *et al.*, 1988, 1990; Kendall *et al.*, 1995) compared with uncultivated plots, but effects are variable in different years and sites (Glen *et al.*, 1988). Non-inversion methods of tillage, such as minimum tillage with tines or disc, or single-pass cultivation systems, such as that with the Dutzi cultivator, generally have less effect on gastropod populations than ploughing combined with subsequent cultivations to produce a seed-bed for cereals (Glen *et al.*, 1988, 1994b, 1996; Kendall *et al.*, 1995). In long-term experiments, the numbers of gastropods in plots under non-inversion tillage regimes were generally intermediate between the high numbers in zero-tillage plots and low numbers in ploughed plots (Kendall *et al.*, 1995; Symondson *et al.*, 1996).

The conclusion that emerges from these studies is that the greater the number of cultivation operations and the more intensive the method of cultivation, the more likely it is that gastropod numbers will be reduced substantially. However, even where tillage results in substantial reductions in populations, sufficient gastropods may still survive to cause severe damage to cereal seeds and seedlings, as shown, for example, by Glen *et al.* (1990).

DRAINAGE. Since gastropods are moisture-dependent animals, Martin and Kelly (1986) concluded that good drainage may reduce the risk of gastropod damage to winter cereals. However, experimental evidence suggests that drainage of soils to prevent waterlogging can improve survival and reproductive success. Carrick (1942) found that *D. reticulatum* laid few eggs in soil that was 100% saturated with water and those few eggs that were laid failed to hatch. Moreover, Stephenson and Bardner (1977) reported that, when soil was flooded for 34 days in winter, substantial numbers of *D. reticulatum*, *A. ater* and *A. hortensis* agg. were killed.

Effects of natural enemies on gastropod populations in cereals

There is little published information on the impact of natural enemies on gastropod populations in cereals in western Europe. However, as noted earlier, substantial population declines, during periods of apparently favourable weather and following 3 years or more with relatively high gastropod populations (Glen *et al.*, 1988, 1996), suggest that natural enemies may play a role in regulating numbers below the carrying capacity of the environment. The identity of the natural enemies that may be involved is not currently known.

A wide range of vertebrate and invertebrate predators are known to feed on gastropods (see Port and Port, 1986; Barker, 2002). Polyphagous predatory carabid beetles are the group considered most likely to have a substantial impact on gastropod populations in cereal fields (Symondson, 2002). Burn (1988) recorded more gastropods (mainly *D. reticulatum*) in traps in areas of cereal crops that had been surrounded by barriers to exclude polyphagous predatory beetles than in areas where the numbers of these predators had not been manipulated. Evidence is accumulating to show that one species of carabid beetle that is widespread and common in cereal fields, *Pterostichus melanarius* (Illiger), is an important predator of gastropods. Stephenson (1965) showed that *P. melanarius* could eliminate *D. reticulatum* from outdoor enclosures. Symondson *et al.* (1996) showed that gastropods (mainly *D. reticulatum* and *A. intermedius*) were important prey of *P. melanarius* in an arable field during the period from July to September, immediately before a crop of winter wheat was sown. Polyclonal antibody analysis demonstrated that, on average, 80% of *P. melanarius* adults had fed on gastropod tissue. Moreover, the numbers of beetles recorded in pitfall traps and the amount of gastropod material in the guts of these predators was positively correlated with the biomass of gastropods m^{-2} in soil samples. At the same experimental site, trends in the numbers and nutritional status of *P. melanarius* over a 5-year period from 1992 to 1996 were consistent with *D. reticulatum* and *A. intermedius* being important prey. When numbers of these gastropods were low, this predator was unable to maintain its numbers or nutritional status on alternative prey (Symondson *et al.*, 2002). Recent studies (Bohan *et al.*, 2000a) indicate that predation by *P. melanarius* can reduce the rate of growth of populations of *D. reticulatum* and *A. intermedius* in a spatially density-dependent manner in cereal fields during the summer months, thus possibly contributing to population regulation and reducing the risk of damage to autumn-sown cereal crops.

Gastropod feeding rate

Availability and accessibility of cereal seeds and seedlings

Gastropod activity on the soil surface in cereal fields is dependent on temperature and soil surface moisture (Young and Port, 1989, 1991; Yang *et al.*, 1991, 1993; Chabert, 1999). Furthermore, their activity is closely correlated with the severity of grazing damage to wheat seedling leaves (Glen *et al.*, 1993). However, damage to cereal seeds and seedlings before emergence, the most important damage, is not correlated with gastropod surface activity, estimated by bait-trapping, between sowing and emergence (Glen *et al.*, 1993). This latter damage is more dependent on the biomass of gastropods in the soil, together with the availability and accessibility of seeds.

Wheat is especially vulnerable to damage at establishment if seed-bed conditions enable the gastropods to move through the soil and locate the seeds and young seedlings. Field surveys have shown that winter wheat sown in a cloddy seed-bed in soil with a high clay or silt content is especially susceptible to damage (Gould, 1961; Moens, 1980), because of the availability of air spaces between soil aggregates. Moens (1989) emphasized the importance of seed cover in determining the severity of damage to wheat seeds. Consolidation of cloddy seed-beds often reduces the severity of damage. Gastropod damage to cereals is characteristically less severe around field edges (headlands) than in the middle of the field, because machinery turning at the edge of the field consolidates the soil (Gould, 1961). The influences of seed-bed conditions on the accessibility of wheat seeds to *D. reticulatum* (Stephenson, 1975; Moens, 1983, 1986; Davies, 1989), *A. hortensis* agg. and *T. budapestensis* (Davies, 1989) have been demonstrated in the laboratory.

Stephenson (1975) noted that damage by *D. reticulatum* to wheat seeds sown at 20–38 mm depth in trays was considerably less than damage to shallower-sown seeds (13 mm). However, he suggested that deeper sowing would be unacceptable in practice as a means of reducing damage, because it would result in delayed emergence, which, in turn, would prevent wheat plants from becoming established before winter.

It has also been considered (Gair *et al.*, 1987) that deeper sowing, by increasing the time to emergence, would make the seeds and seedling vulnerable to damage for a longer period. However, a series of three field experiments (Glen *et al.*, 1989, 1990, 1994b) has shown clearly that sowing at 40–50 mm depth in coarse seed-beds during autumn resulted in substantial reductions in gastropod damage compared with shallow sowing (20–25 mm). No appreciable delay in emergence was associated with the 40–50 mm sowing depth in these experiments, and a yield benefit from the increased sowing depth were observed in 1 year (Fig. 12.2).

Glen *et al.* (1989) showed that the percentage of wheat seeds killed by a mixed-species gastropod community in different seed-beds in a clay soil was directly related to the biomass of gastropods living in the upper 100 mm of soil (Fig. 12.3A) (damage was less well correlated with numbers). Furthermore, per cent kill was also inversely related to the depth of seed placement (Fig. 12.3B) and the percentage of fine soil aggregates (< 6 mm) in the seed-bed (Fig. 12.3C). It thus seemed that gastropod biomass in the soil (*S*) provided a measure of the potential for kill of wheat seeds, but the potential was diminished with greater sowing depth (*D*) and a greater percentage of fine soil aggregates (*F*) in the seed-bed. The influence of these three factors on the percentage of wheat seeds killed by gastropods (*P*) could be described in a simple model:

$$P = \frac{a\sqrt{S}}{DF}$$

where a is a constant. In the experiment of Glen *et al.* (1989) this model accounted for 94% of the variance in seed kill among nine combinations of seed-bed tilth and consolidation (Fig. 12.3D). This model indicates that, at the median gastropod biomass recorded in this experiment (1.6 g m^{-2}), the combined effects of seed-bed tilth and sowing depth together would have resulted in the percentage of seeds killed by gastropods ranging from as little as 5% to as much as 24%. Although, as described above, other work has established that seed-bed consolidation can reduce seed kill by gastropods, Glen *et al.* (1989) noted higher seed kill in seed-beds that had been consolidated before sowing than in unconsolidated seed-beds. This was because consolidation before sowing resulted in seeds being sown at shallower depth than in looser seed-beds, where drill penetration was greater. Glen *et al.* (1989) also noted that consolidation by rolling after drilling had no significant effect on the percentage of seeds killed, because rolling the soil failed to break down soil aggregates, a possibility also noted previously by Stephenson (1975) in the laboratory.

Palatability

Differences in susceptibility of wheat, barley and oat seeds are due, at least in part, to the lack of an outer seed coating on wheat seeds (most susceptible), compared with barley and oat seeds (least susceptible). In

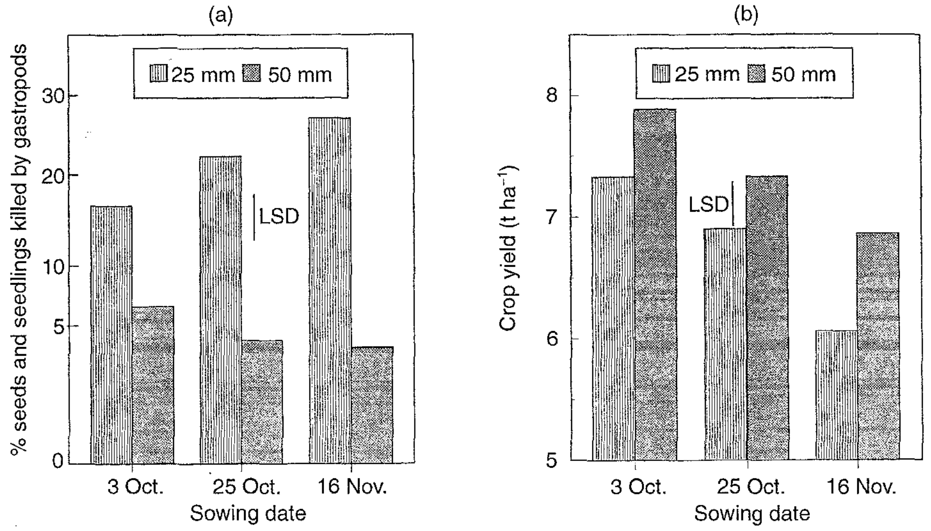
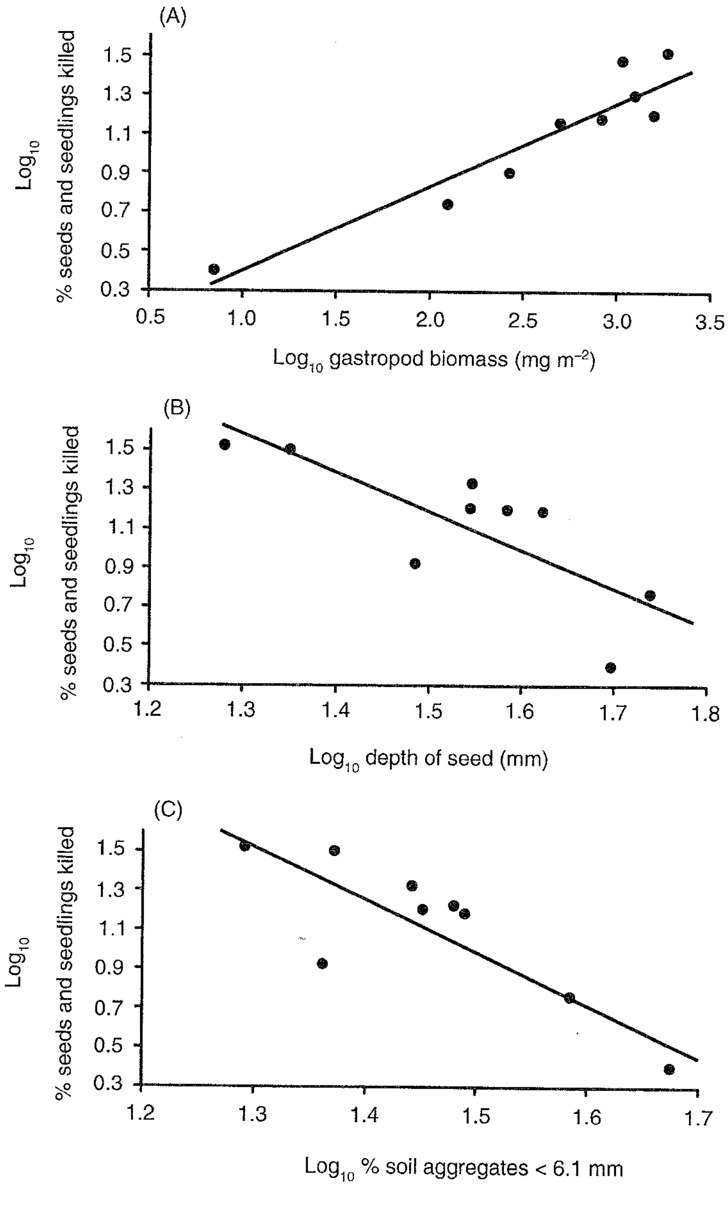


Fig. 12.2. Relationship between sowing depth and (a) percentage of seeds and seedlings killed by gastropods (square-root scale), (b) crop yield for wheat (*Triticum aestivum* Linnaeus) (Gramineae) sown at three dates in autumn 1989 (adapted from Glen *et al.*, 1994b). LSD, least significant difference ($P = 0.05$).

laboratory studies, Spaull and Eldon (1990) and Evans and Spaull (1996) found differences in the degree of grain hollowing in different wheat cultivars by *D. reticulatum*. However, Cook *et al.* (1996) failed to find significant differences between wheat cultivars in laboratory experiments that included the most and least preferred cultivars in the above experiments, and concluded that cultivars possess no inherent differences in palatability to *D. reticulatum*.

Availability of alternative food

At the time when crops are most susceptible and vulnerable to gastropod damage, residues of the previous crop are generally the most abundant alternative food. However, gastropod numbers tend to increase and their damage is often severe where large amounts of crop residues are returned to the soil. These observations indicate that the availability of food in the form of crop residues does not greatly influence the severity of damage to establishing wheat crops. This may be simply because high gastropod numbers outweigh any tendency for individuals to feed on alternative food. However, the known preference of *D. reticulatum* for novel foods (Frain and Newell, 1982), in this case wheat seeds and seedlings, may also be important. Recent laboratory and field studies (Cook *et al.*, 1996, 1997) do indicate, however, that certain weeds common in arable fields, such as dandelion (*Taraxacum officinale* Weber) (Asteraceae), are highly preferred food for *D. reticulatum*, in comparison with wheat seedlings, and their presence can reduce damage to wheat crops.



Vulnerability of crop to damage

Specific vulnerability and duration of vulnerable stages

Wheat is most vulnerable to gastropod damage shortly after drilling (Moens, 1983, 1986, 1989). As soon as the seed has imbibed water (Zadok's growth stages (GS) 02–05), gastropods gain entry to and are able to hollow the developing embryo (Fig. 12.4A). As noted above, gastropods

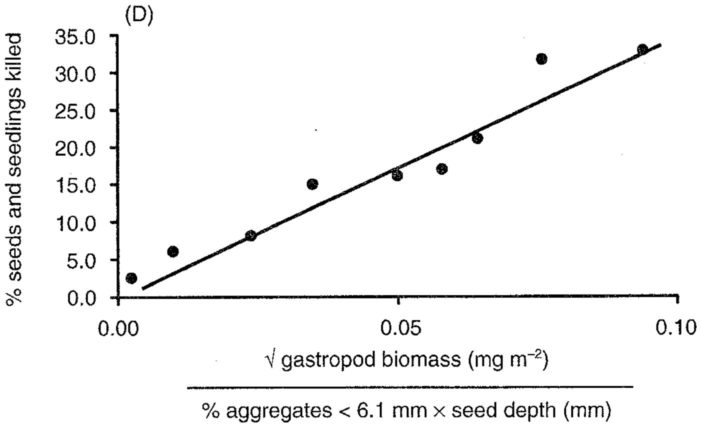


Fig. 12.3. Percentage of wheat (*Triticum aestivum* Linnaeus) (Gramineae) seeds and seedlings killed by gastropods in relation to (A) the biomass of gastropods in the top 10 cm of soil ($P < 0.001$, accounts for 87% of variance), (B) depth of seed in the soil ($P < 0.05$, accounts for 56% of variance), (C) the percentage of fine soil aggregates in the top 10 cm of soil ($P < 0.01$, accounts for 67% of variance) and (D) these three factors combined ($P < 0.001$, accounts for 94% of variance) (Glen *et al.*, 1989).

are only able to find seeds that are poorly covered by soil (Moens, 1983, 1986). Such seed is not only found more readily, but also germinates more slowly and thus remains at the most vulnerable stage for longer than well-covered seed (Moens, 1983). Vulnerability diminishes sharply once the coleoptile starts to grow (GS 07–09), because the coleoptile sheath acts as a mechanical barrier protecting the young shoot as it grows to the soil surface. The shoots are often damaged once they emerge from the coleoptile, but provided that young plants are growing well they can withstand considerable above-ground grazing damage to the young leaves and shoots. The growing points remain below ground at the base of the shoot, and are protected from damage if there is adequate soil cover. This protected meristematic tissue is in marked contrast to that situation in dicotyledonous crops, such as oilseed rape (see Moens and Glen, Chapter 19, this volume). As noted previously, where cereal seed is poorly covered by soil, gastropods can kill the growing point after seedling emergence by eating through the base of the shoot (Fig. 12.4B).

Cereal seedlings are especially at risk from gastropod damage if chlorophyll losses are not compensated for by growth (Moens, 1989). Factors resulting in low vigour include lack of moisture for seed germination and seedling growth, due, for example, to poor soil cover in cloddy seed-beds. Slow growth can also be caused by soil capping or overly compacted seed-beds, which result in a poor supply of oxygen to the plant roots. Waterlogging of soil and low soil temperatures are other common causes of slow growth.

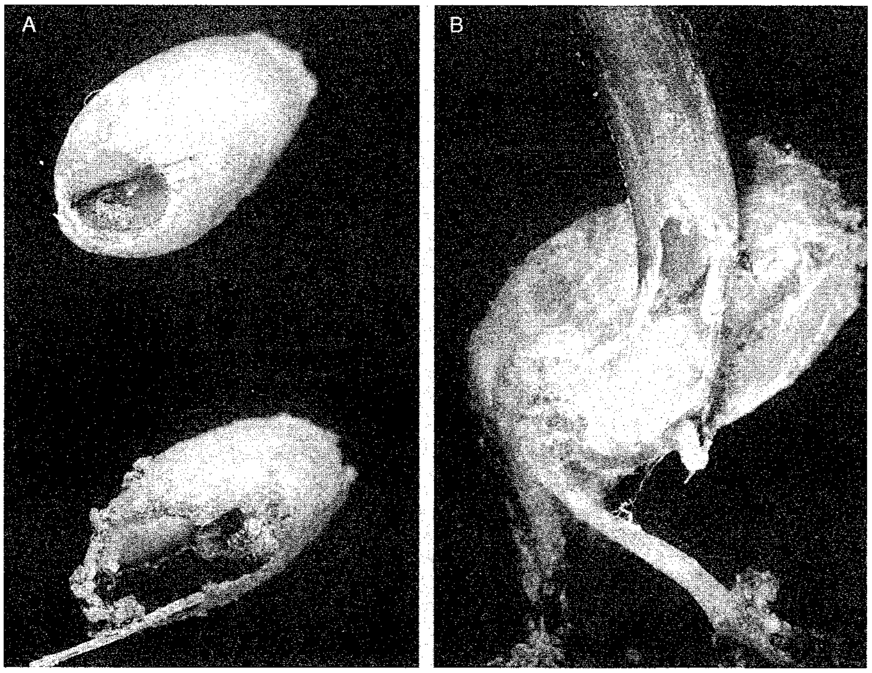


Fig. 12.4. (A) Wheat (*Triticum aestivum* Linnaeus) (Gramineae) seed with characteristic gastropod damage, where the embryo and part of the endosperm is destroyed, and (B) wheat seedling where the base of the young shoot has been excavated and the meristem tissue destroyed.

Sowing date

Cereals sown later in the autumn are generally at greater risk of gastropod damage than cereals sown earlier (Martin and Kelly, 1986; Port and Port, 1986; Glen *et al.*, 1993). This is probably because there is a greater likelihood in early autumn of farmers being able to prepare fine firm seed-beds that discourage attack, compared with later in autumn, when colder, wetter conditions usually prevail, making preparation of fine, firm seed-beds difficult or impossible. However, damage is not inevitably more severe in late autumn than in early autumn. For example, Glen *et al.* (1990, 1994b) noted no significant difference in gastropod damage to wheat sown in early, mid- or late autumn in two separate years, because gastropod biomass, seed-bed tilth and seed depth showed little change as autumn progressed. Substantial declines in gastropod populations in autumn have been observed in certain fields in some years (Glen *et al.*, 1988, 1994a,b; Wilson *et al.*, 1994a). Thus, in these sites, the risk of gastropod damage would have diminished considerably in late autumn, other things being equal.

Relationship between gastropod damage and yield

There is relatively little information on the relationship between the level of gastropod damage and reductions in crop yield, despite its critical importance to the development of pest-management strategies. The relationship between damage and yield is undoubtedly greatly influenced by plant vigour and plant population. It is well known that, provided plant growth is not restricted by poor soil conditions, cereal crops can compensate for considerable reductions in plant population that may result from losses of seeds and seedlings, without appreciable reductions in yield. This capacity for compensation in cereals depends greatly on tillering ability, which can differ markedly among cultivars, especially for barley. Jessop (1969) simulated gastropod damage to a winter-wheat crop by removing plants at random from drill rows. He found that 25%, 75% and 92% removal resulted in yield reductions of only 4%, 19% and 34%, respectively. However, because gastropod damage is usually patchy within a field, yield losses are likely to be different and probably greater than those predicted from this simulation experiment. Moreover, gastropod damage is often accompanied by soil conditions that result in poor crop growth and therefore restricted ability of cereal plants to compensate for losses caused by these pests. Christian *et al.* (1999) recorded losses of 13–47% of wheat seeds and seedlings to gastropods (mainly *D. reticulatum*, *A. intermedius* and *A. silvaticus*) after direct drilling into stubble or straw in autumn in 1982 to 1984. These losses were associated with yield reductions of 36–52%, compared with the yield on plots direct-drilled after straw burning, where ≤ 6% seeds and seedlings were lost to gastropods. Glen *et al.* (1994b) reported a yield reduction of about 9% associated with 20–30% plant losses caused by gastropods (Fig. 12.2). Although in both cases it is not possible to directly attribute these yield losses to gastropod damage, the findings emphasize that damage in the field is often associated with substantial yield losses.

Management of Gastropod Damage to Cereals

As described above, the risk of gastropod damage to winter wheat is considerably influenced by several cultural practices. However, most cannot be considered as useful control measures and, as pointed out by Martin and Kelly (1986), farmers have many factors other than gastropod damage to take account of in making decisions on cultural measures. For example, the risk of gastropod damage is substantially greater after dense leafy crops, such as oilseed rape and pea, than after fallows or crops such as potato and sugar beet (*Beta vulgaris* Linnaeus; Chenopodiaceae), which leave bare soil between rows. However, crop rotations have to be designed to fulfil multiple aims (Jordan and Hutcheon, 1996). For this reason, farmers often choose to grow crops despite an awareness of the associated pest risks (Glen *et al.*, 1996). Similarly, farmers often choose cultivation methods, crop disposal practices and sowing times that increase the risk of gastropod damage. Knowledge of the risks associated with such practices is, however, important in assessing the need for control measures, which are currently based on integration of cultural and chemical techniques.

Cultural control

Cereal farmers aim to prepare fine, firm seed-beds to reduce the risk of seeds and seedlings being killed by gastropods. However, it is important to stress the limitations of this method of control. First, farmers must be careful not to produce such a fine seed-bed that the soil 'caps' as a result of heavy rainfall during the winter months, with resulting poor growth due to restricted air supply to the roots. Secondly, on soils with a high clay or silt content, it is often not possible to produce a fine seed-bed, because when such soil is too dry or too wet it does not break down into fine aggregates but remains as coarse clods. In such situations rolling is a recommended method of control, because clods are usually broken down to give finer aggregates (Stephenson, 1975) or squashed, thus reducing the size of air spaces (Davies, 1989). However, rolling has severe limitations as a practical method of controlling gastropod damage. In soil with hard dry clods, rolling may not be beneficial because the clods are not affected (Stephenson, 1975; Glen *et al.*, 1989). Moreover, rolling is not possible in wet soil conditions because of smearing and the risk of soil capping.

Where it is necessary to drill cereal seeds into a coarse, cloddy seed-bed, the severity of gastropod damage can be greatly reduced by increasing the drilling depth from the normal 30 mm to 40 or 50 mm (Glen *et al.*, 1990, 1994). This increased drilling depth is readily achieved, does not cause an unacceptable delay in emergence and may in some cases speed germination, because there is often more moisture as well as better soil cover of seeds at this depth in cloddy seed-beds (Wibberley, 1989). Glen *et al.* (1990) showed that drilling at 40 mm depth rather than 20 mm depth was as effective as a broadcast application of molluscicide bait pellets in reducing the kill of wheat seeds and seedlings (Fig. 12.5). As previously noted, drilling at 50 mm depth not only reduced gastropod damage in one experiment, but was also associated with an increase in yield (Fig. 12.2).

The extra time required for emergence by deeper sowings has little impact on the severity of damage, because wheat is most vulnerable to gastropod damage as seeds and in the early seedling stages shortly after the shoot has started to grow (Moens, 1989). Although shoots from deeper-sown seeds have to grow through the layers of soil where gastropods are most active, by then they are past the most vulnerable stage and, as explained below, they can generally be protected by a broadcast application of molluscicidal bait pellets.

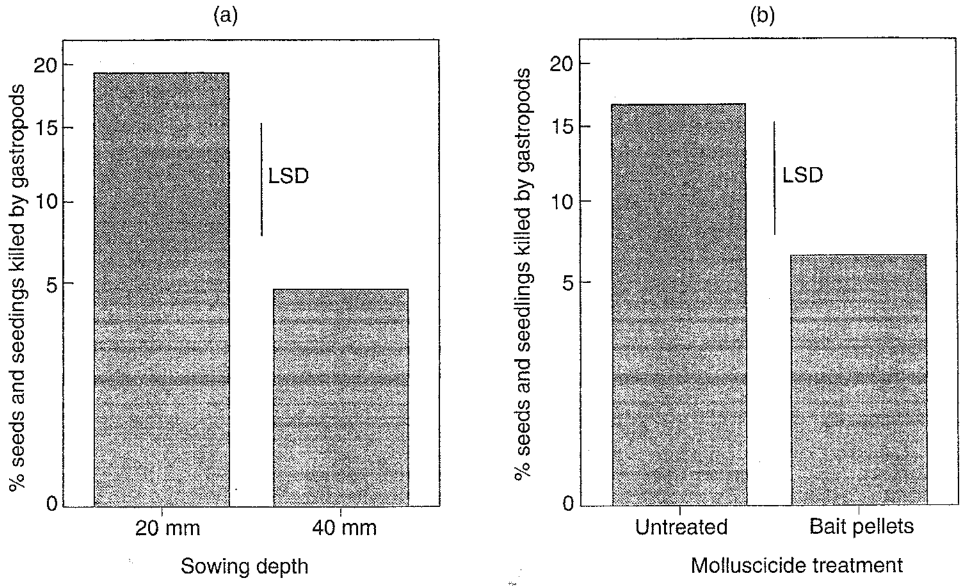


Fig. 12.5. Percentage of wheat (*Triticum aestivum* Linnaeus) (Graminaceae) seeds and seedlings killed by gastropods (square-root scale) as influenced by (a) sowing depth and (b) molluscicidal bait pellets applied as a broadcast treatment on the soil surface immediately after sowing (after Glen *et al.*, 1990). LSD, least significant difference ($P = 0.05$).

Although the presence of certain weed species has been shown to reduce damage to wheat seedlings, it is unlikely that farmers will ever deliberately sow weeds in order to reduce gastropod damage. However, it may be possible to grow companion crops instead of weeds to reduce the severity of gastropod damage. For example, George *et al.* (1995) demonstrated in the laboratory that damage to wheat seedlings by *D. reticulatum* was reduced when wheat was grown together with white clover (*Trifolium repens* Linnaeus) (Fabaceae). This approach has yet to be fully developed and used by farmers as a gastropod control strategy.

Biological control

The nematode *Phasmarhabditis hermaphrodita* (Schneider) (Rhabditidae) is a parasite capable of killing Agriolimacidae, Arionidae, Milacidae and other gastropods (Wilson *et al.*, 1993). It has been developed as a commercial biological control agent and has been used successfully to protect a range of crops from gastropod damage (Glen and Wilson, 1997), including winter wheat (Glen *et al.*, 1994a; Wilson *et al.*, 1994a,b, 1996; Hass *et al.*, 1999). The effectiveness of the nematode is dose-dependent. In winter wheat, a dose of 3×10^9 ha^{-1} was found to give protection to seeds and seedlings similar to that provided by a broadcast application of methiocarb bait pellets applied immediately after drilling (Wilson *et al.*, 1994a). In dry soil conditions, shallow cultivation by tines after nematode application was found to result in improved efficacy, probably as a result of protection of the nematodes from desiccation (Wilson *et al.*, 1996). Hass *et al.* (1999) noted that the machinery used for shallow incorporation of nematodes can have a profound influence on nematode efficacy. Thus, field experiments have demonstrated that it is technically feasible to use *P. hermaphrodita* for control of gastropod damage in cereals. It is compatible with the cultural control measures outlined above and it has two important advantages over chemical control. First, it does not affect non-target invertebrates or vertebrates (other than non-pest gastropod species) (Glen and Wilson, 1997) and, secondly, it is not adversely affected by heavy rain even in conditions where molluscicidal bait pellets are rendered ineffective (Hass *et al.*, 1999). However, *P. hermaphrodita* is not currently used for gastropod control in cereals because of its high cost, rendering it non-competitive with chemical molluscicides, and the limited storage life of this biocontrol agent, even under refrigerated conditions. For these reasons, its use is likely to be restricted to the home-garden market and high-value horticultural crops for the foreseeable future (Glen and Wilson, 1997).

Chemical control

Control of gastropod damage in west European cereals relies mainly on the application of molluscicidal bait pellets containing metaldehyde, methiocarb or thiodicarb as the active ingredient. Pellets are normally applied shortly before or after drilling as broadcast treatments on the soil surface, or the pellets are applied as an admixture with the seeds at drilling. Laboratory studies have shown that, following an encounter, *D. reticulatum* and *A. distinctus* are more likely to feed on molluscicidal pellets than on wheat seeds (Bourne *et al.*, 1988; Bailey and Wedgwood, 1991). However, the amount of bait pellet eaten is reduced in the presence of wheat seeds (Bourne *et al.*, 1988). This suggests that molluscicidal bait pellets should be applied before wheat seeds are available or that, if they are applied when wheat seeds are sown, it is important to maximize the availability of pellets and minimize the availability of wheat seeds, as outlined below.

Laboratory and field studies have demonstrated that it is feasible to protect cereal seeds and seedlings from gastropod damage by applying molluscicidal or repellent chemicals to seeds (Gould, 1962; Scott *et al.*, 1984; Ester and Nijënstein, 1995; Ester *et al.*, 1996; Watkins *et al.*, 1996; Nijënstein and Ester, 1998). Certain fungicidal seed dressings also protect seeds from gastropod damage (Moens *et al.*, 1992). However, no molluscicidal seed treatments have yet been made available commercially. Reasons for this are not always clear but considerations such as potential toxicity of dressed seeds to seed-eating birds are important in some cases.

Timing and placement of molluscicide bait applications

The most reliable control of gastropod damage to winter wheat is generally achieved by applying molluscicide bait pellets shortly before or after sowing (Glen *et al.*, 1992a; Gratwick, 1992; Port *et al.*, 1992). Gratwick (1992) states that the best results are generally obtained by applying bait pellets before sowing, when gastropods are active on the soil surface, and then avoiding further tillage for at least 3 days after treatment. This advice is consistent with the recommendation by Bourne *et al.* (1988) described above. However, because of the importance of timely sowing in maximizing crop establishment, growers are not recommended by Gratwick (1992) to delay sowing simply to apply bait pellets before drilling. In most situations the best practical option is to broadcast bait pellets on the soil surface at or immediately after drilling (Gratwick, 1992). Experimental applications of bait pellets to the stubble of a previous crop have given relatively poor results compared with applications closer to the time of seed sowing, which are more effective probably because they are targeted on residual populations already reduced by tillage (Port *et al.*, 1992). Typically, molluscicide applications to wheat crops kill only about 50% of the gastropod population that is resident in the upper 10 cm of soil at the time of application, with a slightly greater reduction in biomass of *c.* 60% (Glen and Wiltshire, 1986; Wiltshire and Glen, 1989; Glen *et al.*, 1991). In addition, gastropod eggs in soil are unaffected by molluscicides. Thus, gastropod populations often have sufficient time to recover from treatments applied to stubble before a wheat crop is sown. Nevertheless, there appear to be differences in the resilience of gastropod species. Glen *et al.* (1992b) reported recovery of *D. reticulatum* and *A. intermedius* populations within a few months of autumn molluscicide treatment, but year-long reductions in *A. silvaticus* and *A. subfuscus*.

Application of molluscicidal bait pellets to the soil surface at seed sowing protects seedlings from grazing damage after plant emergence, in addition to protecting seeds and seedlings before emergence (Glen *et al.*, 1990, 1992a). If gastropod grazing damage to emergent seedlings causes concern, it may be worthwhile to apply pellets after crop emergence to reduce plant losses, particularly if the crop has been thinned by seeds being killed before emergence (Gratwick, 1992). However, by the time that damage becomes evident after emergence, it may be too late to take the most effective action (e.g. Glen *et al.*, 1992a). This emphasizes the importance of reliable prediction of the risk of gastropod damage and the need for control measures.

Molluscicidal bait pellets can either be applied to the soil surface or drilled with wheat seed. The latter option appears attractive, because the bait pellets are close to the seeds, which are the most vulnerable stage. In addition, bait pellets drilled with seeds are less likely to kill non-target invertebrates and vertebrates than pellets broadcast on the soil surface (Kennedy, 1990; Johnson *et al.*, 1991). However, bait pellets drilled with wheat seeds may be unavailable to gastropods (Glen *et al.*, 1992a), especially if the recommended seed-cover measures are adopted to protect seeds from feeding gastropods. Shallow-sown seeds in a coarse seed-bed, which are vulnerable to gastropod damage, can be protected by bait pellets drilled with them, but this protection may be no better than would be achieved by drilling seed a little deeper in a coarse seed-bed (Glen *et al.*, 1992a). In order to improve the protection from seed kill obtained by deeper drilling alone, bait pellets should be broadcast on the soil surface after drilling a little deeper than normal (Glen *et al.*, 1990, 1992a).

Damage Forecasting and Risk Assessment

Because of the importance of taking appropriate action before or shortly after cereal crops are sown in order to provide the best protection from gastropod damage (Glen *et al.*, 1992a; Gratwick, 1992; Port *et al.*, 1992), a reliable system of forecasting gastropod damage to cereals would be extremely valuable to farmers and consultants. Experience clearly indicates that, by the time that potentially severe damage becomes evident, either as gaps in the rows of an emerging wheat crop or as grazing damage to seedlings, it is already too late to take the most effective action. The relationships in Fig. 12.3 clearly indicate the importance of gastropod biomass in soil, seed-bed tilth and sowing depth in assessing the risk of damage. However, because direct methods of estimating gastropod biomass are too slow and labour-intensive for commercial use, consultants and growers currently rely on refuge traps, whose catch provides a composite index of gastropod abundance and the degree of surface activity. Whilst gastropod activity on the soil surface can be predicted on the basis of temperature and surface moisture (Young and Port, 1989, 1991; Yang *et al.*, 1991, 1993; Chabert, 1999), surface activity is almost certainly considerably disrupted by the cultivations involved in seed-bed preparation and, as pointed out earlier, gastropod activity on the soil surface at drilling and between drilling and emergence is poorly correlated with the severity of seed hollowing by these animals (Glen *et al.*, 1993).

In a study throughout the UK, Glen *et al.* (1993) found that the best predictor of damage was simply the peak number of gastropods trapped at times when the soil surface was visibly moist, during the period from July until the soil was disturbed by cultivation. However, even this predictor was imprecise, accounting for only 26% of the variance in damage, and the threshold trap catch for molluscicide treatment based on this predictor inevitably includes a large safety margin. Thus, even if farmers use this prediction method, it is likely that many fields treated with molluscicide do not have sufficiently high gastropod numbers to justify such treatment. Thus, there is considerable scope for improvement in damage forecasting. Current effort to improve forecasting is focused on improved understanding of the spatial and temporal dynamics of gastropod populations in arable crops (Bohan *et al.*, 1997, 2000a,b; Shirley *et al.*, 1997, 1998, 2001), including the influence of weather (Chabert, 1999). However, improved practical methods of assessing gastropod biomass in soil are also needed in order to give better predictions of the severity of damage and the need for control measures. It may be possible to assess gastropod biomass in soil by using traps, such as those described by Hommay and Briard (1988) or Young *et al.* (1996), to assess surface activity, in combination with a simulation model of population dynamics, such as that for *D. reticulatum* described by Shirley *et al.* (2001). Young *et al.* (1996) have stressed the desirability of using non-toxic baits rather than molluscicide baits (as used, for example, by Glen *et al.*, 1993) in traps.

Because gastropod surface activity is strongly correlated with grazing damage to seedlings (Glen *et al.*, 1993), weather information (Young and Port, 1989, 1991; Chabert, 1999) is of considerable value in helping to decide on the need for and likely success of control measures after crop emergence.

Conclusions

Gastropod damage to cereals is influenced by several interacting factors and understanding of these has improved steadily in recent years. Because of this and improvements in cultural and chemical control measures, it might be expected that problems would be considered to be less severe now than in the past. Survey data from 1982 to 1996 indicate no trend in molluscicide use in cereals (Thomas *et al.*, 1997). However, farmers' perception of the severity of gastropod problems in cereals had, if anything, increased in the late 1990s. Reasons for this are not fully clear, but a number of plausible contributory factors can be proposed.

First, as stressed by Martin and Kelly (1986), farmers are well aware of the need to produce an adequate plant stand in order to achieve sufficient yield to provide profit, and they are alert to the potential for gastropods to prevent such a stand being achieved. It is sometimes suggested that farmers could simply increase the seeding rate in order to compensate for anticipated losses from gastropods. However, this is not a sensible alternative to molluscicide use, because: (i) if damage is less severe than anticipated, then an overly dense stand could lead to yield loss; and (ii) in severe damage a greater initial plant density could not compensate for losses.

Secondly, cereal growers and consultants frequently express the opinion that gastropods have become more abundant in recent years. Much evidence has been presented in this chapter to show that modern agronomic practices could be responsible for increased gastropod abundance. Similarly, trends in weather patterns (mild winters and wet summers) in many recent years have been favourable to gastropods (Chabert, 1999). Reductions in the impact of natural enemies and other biotic constraints on gastropod population growth could also be responsible, perhaps mediated by changes in agricultural practices. This 'natural enemy' hypothesis has not yet been properly explored. However, evidence is steadily accumulating that natural enemies, such as carabid beetles, can reduce the growth rate of gastropod populations (Bohan *et al.*, 2000a; Buckland and Grime, 2000; McKemey, 2000; Symondson *et al.*, 2002) and further research is warranted.

Thirdly, while the widespread adoption of cultural measures to reduce kill of seeds and seedlings has improved crop stand at emergence, it seems that, in fields with an abundance of gastropods, this has sometimes resulted in attack being only delayed until after emergence, with severe grazing and consequent loss of plant stand.

Fourthly, although molluscicide bait pellets are normally highly effective in reducing the severity of damage, many farmers and consultants continue to report inadequate control. The reasons for this are not known and must be identified. For example, because molluscicides typically kill only about 50% of the population in the soil, then, where gastropods are abundant, enough may survive treatment to inflict severe damage. Gastropods hatching from eggs or resuming normal surface-activity patterns some time after the disruption caused by seed-bed preparation and after molluscicides have ceased to be effective may also be responsible. It is also possible that, as suggested by Hass *et al.* (1999), molluscicidal bait pellets are rendered ineffective when heavy rain falls shortly after bait pellets are applied, with pellets becoming covered in mud splash or washed into soil crevices and hidden from gastropods. If this is so, then in some years it would be possible to adjust timing of bait-pellet application in order to avoid exposure of bait pellets to such rain. In very wet autumns this may not be achievable, but nevertheless knowledge of the effects of rainfall would indicate which molluscicide applications are likely to be ineffective and where further treatment may be necessary. Unfortunately, biological control using the nematode *P. hermaphrodita*, which Hass *et al.* (1999) found to be highly effective in wet conditions, is not economically viable as a practical control measure in cereals.

It must be emphasized that the above suggestions are merely pointers to future research needed to provide the improved understanding of gastropod population ecology and behaviour and the factors that influence molluscicide efficacy in cereal crops. This new understanding will not be easily achieved. However, the potential benefits of better prediction and control of gastropod damage make such studies well worthwhile. Precise estimation of risk will lead to a reduction in unnecessary molluscicide usage, which will result in less widespread environmental side-effects as well as lower cost to the farmer. Growers will also be able to concentrate their efforts in fields where the real risk is high and adequate control is difficult to achieve. More reliable and economic control would have obvious benefits for cereal growers. In addition to investigations into ways to achieve better use of existing control methods, new methods, such as seed treatment, should continue to be explored.

Acknowledgements

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