The biology and non-chemical control of Fat-hen (*Chenopodium album* L.)

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Fat-hen
(biacon weed, common lamb's quarters, drought weed, frost-blite, goosefoot, lamb's tongue, meld-weed, muckweed, white goosefoot, wild spinach)
***Chenopodium album* L.**

Occurrence
Fat-hen is a summer annual present throughout Britain but less frequent in the north and west (Williams, 1963). It is not recorded above 1,250 ft in the UK (Salisbury, 1961). In early surveys in Bedfordshire, Norfolk and Hertfordshire, fat-hen was distributed over all soil types (Brenchley, 1913). It was characteristic of light sandy soils but also frequent on clay (Brenchley, 1911). It was scarce on gravel and not recorded on chalk. It grows best on fertile soils but will tolerate most soil types (Weber, 2003). It attains great size and vigour on good cultivated loams or clays where it often occurs in large numbers (Long, 1938). It is common on sandy loams but less frequent on calcareous soils.

Fat-hen is one of the most troublesome annual weeds and is known by many common and local names (Long, 1938). It is a frequent garden weed (Copson & Roberts, 1991). It ranks as an important weed in potatoes and sugar beet worldwide but is less common in cereals, particularly in winter cereals. In a survey of arable weeds in Britain 1971-73, fat-hen was common to abundant in half the survey areas and scarce in the rest (Chancellor, 1977). In a survey of weeds in conventional cereals in central southern England in 1982, fat-hen was found in 2, and 3% of winter wheat, and spring barley respectively but not at all in winter barley (Chancellor & Froud-Williams, 1984). It is more frequent in spring-sown than autumn-sown crops (Granström, 1967). It was relatively common in a survey of weeds in spring cereals in N E Scotland in 1985 (Simpson & Carnegie, 1989). Fat-hen was one of the most frequent weed species present in conventional sugar beet crops surveyed in East Anglia in autumn 1998 (Lainsbury *et al.*, 1999). It was a common species in the field margins too.

In a study of seedbanks in some arable soils in the English midlands sampled in 1972-3, fat-hen was recorded in 56% of the fields sampled in Oxfordshire and 75% of those in Warwickshire (Roberts & Chancellor, 1986). Fat-hen seed was found in 33% of arable soils in a survey in Scotland in 1972-1978 (Warwick, 1984). It accounted for 10% of the seeds in the soil seedbanks. It was also a common weed in a seedbank survey in swede turnip fields in Scotland in 1982 (Lawson *et al.*, 1982). It was found in 58% of fields sampled often in moderate numbers. In a seedbank survey in Denmark in 1964, fat-hen was one of the most frequent seeds recorded with an average of 1,500 seeds per m^2 (Jensen, 1969). In seedbank studies in arable fields in France too, fat-hen was well represented in the seedbank and in the emerged vegetation (Barralis & Chadoeuf, 1987).

Fat-hen remained relatively widespread in the period between 1978 and 1990 despite increased herbicide use (Firbank, 1999). A study of changes in the weed flora of southern England between the 1960s and 1997 suggests that fat-hen has become more common (Marshall *et al.,* 2003). Fat-hen is one of the most frequent arable weeds in Denmark and is well represented in the vegetation (Streibig, 1988). In Finland there was an increase in the frequency of fat-hen in conventional spring cereals in the period 1980 to 1990 (Hyvönen *et al.,* 2003). This may reflect a change in the rate or type of herbicides used. In a comparison of the ranking of arable weed species in unsprayed crop edges in the Netherlands in 1956 and in 1993, fat-hen had moved up from 10th to 1st place (Joenje & Kleijn, 1994). In a series of 4 national weed surveys made in Hungary between 1950 and 1997, it only moved from 3rd to 4th place in the rankings (Tóth *et al.,* 1999; 1997). In 1993, a survey of the most important weeds according to European weed scientists ranked fat-hen as the most important weed in potatoes, sugar beet and the second most important in vegetables (Schroeder *et al.,* 1993). It was less important in spring cereals and not ranked at all in winter cereals. However, in trials in Denmark 1969-1988, fat-hen was the most frequent weed of spring-sown arable crops (Jensen, 1991).

Fat-hen is a very variable plant and is sometimes treated as an aggregate species. It is known to hybridise with some related species but hybrids are difficult to identify due to the variability of the main species (Clapham *et al*., 1987; Stace, 1997). Some populations of fat-hen in forage maize crops in South Wales and South-west England have developed resistance to the triazine herbicide atrazine (Clay, 1989). Elsewhere, populations have been found with resistance to the herbicide chloridazon (Putwain & Mortimer, 1989). Some fat-hen populations exhibit considerable genetic variability but where repeated herbicide use applies a high selection pressure to a population, phenotypic polymorphism is found to be very low (Al Mouemar & Gasquez, 1983). There is much higher variability in a garden population where there has been little selection pressure. Organic weed management techniques can also apply selection pressure to weeds.

Fat-hen was eaten as a vegetable from Neolithic times till the 16th century when it was replaced by spinach and cabbage (Mitich, 1988). The seeds were ground into flour for bread, cakes and gruel. In Canada it was grown as food for pigs and sheep and was called pig weed (Morse & Palmer, 1925). Despite being used as forage for stock, fat-hen can contain potentially dangerous levels of nitrates (Mitich, 1988). On nitrogen rich soils it may accumulate relatively high levels of nitrate, it also accumulates potassium (Williams, 1963). It extracts large quantities of nutrients from the soil (Hanf, 1970). It contains relatively high levels of calcium but has a high content oxalic acid that can affect dietary calcium bioavailability (Guil *et al.,* 1996). Swine can suffer if they ingest too much fat-hen for example when put in a resown pasture dominated by fat-hen but cases of poisoning are rare (Bassett & Crompton, 1978). Plants contain a high level of ascorbic acid, vitamin C (Barker, 2001). The leaves are a source of ascaridole, an oil used to treat infestations of round worms and hook worms (Mitich, 1988). Fat-hen is an important constituent in the diet of many farmland birds (Lainsbury *et al.,* 1999). It is a frequent birdseed alien (Hanson & Mason, 1985).

Fat-hen may act as a host to the mangold fly and the black bean aphid (Long, 1938; Morse & Palmer, 1925). It can also carry various insect, nematode and virus species that affect important crops (Thurston, 1970). Some of the viruses may be seed borne

(Heathcote, 1970). Transmission of sowbane mosaic virus (SoMV) by seeds of infected plants is 6% (Horváth *et al.,* 2002).

Biology

Fat-hen flowers in the long days from July-September (Long, 1938) but plants mature faster as the days shorten (Williams, 1963). Flowers are wind pollinated and can be self or cross pollinated (Bassett & Crompton, 1978). Seed matures late in the season, from August onwards (Chepil, 1946, Grime *et al.,* 1988). Plants can be found in fruit for 4 months of the year (Salisbury, 1962). The time from germination to fruiting is around 100 days (Guyot *et al.,* 1962).

Seed numbers per plant have been variously quoted at 500 to 20,000 (Guyot *et al.,* 1962), 3,000 (Salisbury, 1961), 20 to 3,500 (Williams, 1963), 3 to 100 (Stevens, 1957), 72,450 (Stevens, 1932; Bassett & Crompton, 1978) and 8,546 to 164,691 with an average of 57,289 (Herron, 1953). In winter cereals the average seed number per plant ranged from 590 to 600, in spring cereals from 980 to 1,012, in red clover and winter rape from 43 to 48 and in root crops from 12,425 to 13,237 (Pawlowski, 1966). Seed numbers per plant varied with the year, the crop and plant density (Grundy *et al.* 2004). Nevertheless, there was a robust relationship between plant dry weight and seed production. The published 1,000 seed weights vary from 0.44 to 1.15 g. Pekrun & Claupein (2006) give the 1,000 seed weight as 0.9 g. Seeds on plants that matured earlier in the season were significantly heavier than seeds on plants that matured later (Cavers & Steele, 1984).

Most mature seeds are black and shiny but around 3% are larger and light brown (Williams, 1963). Four categories of seed have been distinguished; brown smooth, brown reticulate, black smooth, black reticulate. All may be found on the same plant (Williams & Harper, 1965). The percentage of brown seed varies from 1.3 to 2.6%. The 1,000 seed weights of smooth brown seed is 1.55 g and of smooth black is 1.13 g. The black and brown seeds differ in germination requirements and respond differently to chilling and nitrate. Brown seeds germinate rapidly in the presence of water, oxygen and suitable temperatures (Henson, 1970). The radicle emerges within 12-24 hrs. Brown seeds do not require chilling or nitrate to germinate. Black seed is naturally dormant. Black reticulate seeds do not have a chilling requirement but germination of the smooth black seed increases after chilling at 5^{o}C for 21 days. Potassium nitrate also increases the germination of black seed. The level of seed germination increased from 24 to 73% following a 2-month period of moist storage at 5^{o}C (Grime *et al.,* 1981). Germination remained at under 10% in darkness and under a 'safe' green light at both alternating and constant temperature.

Immature seeds are capable of germination and may do so more readily than ripe seed due to their thinner seed coats (Chakravarti & Pershad, 1953). Seed produced in long days is said to be more dormant that seed formed in short days (Hilhorst & Toorop, 1997). Fat-hen seeds may have a light requirement for germination due to the retention of chlorophyll by the maternal tissue that surrounds the developing seed (Cresswell & Grime, 1981). The chlorophyll filters the light that reaches the seeds. Light has a variable effect on germination and this in part depends on seed age and seed source. In germination tests with light filtered through leaves, germination was less under a leafy canopy compared with under diffuse natural light (Taylorson & Borthwick, 1969). When seeds were put to germinate under a leaf canopy or in diffuse white light there was 28% germination under the canopy and 47% in the light (Górski *et al.*, 1977). In Petri-dish tests with seeds maintained under high or low light intensity or in darkness, seeds gave 66% germination in bright light, 48% in low light but only 4% germinated in the dark (Grime & Jarvis, 1976). Seed stratified outdoors in soil overwinter was exhumed and tested for germination in the light, in the dark and in the dark with a 5 second flash of light (Andersson *et al.*, 1997). Seed gave complete germination in the light, 90-95% germination in the dark with a short flash of light and 36-55% germination in darkness. The best chilling treatment for relieving dormancy in imbibed seeds was 4 days in the dark at 4^{o}C (Roberts & Benjamin, 1979). Longer periods of chilling (7-14 days) were needed in the light to achieve good germination. The scarification of seed can significantly increase the level of germination (Deschênes & Moineau, 1972). In Petri-dish tests with seed given alternating or constant temperatures in diffuse light, light had no effect on its own but interacted with alternating temperature to promote germination (Vincent & Roberts, 1977). The response was improved in the presence of nitrate and by chilling. Caussanel (1980) found that germination of brown seeds was indifferent to light or sowing depth but shallow burial to 10 mm was sufficient to reduce seedling emergence from black seeds. In laboratory studies with dry stored seed sown on moist paper or soil in the light there was 6-8% germination at a constant 18-20^{o}C or alternating 20 / 30^{o}C on paper or soil (Cross, 1930-33). At alternating temperatures of 8 / 20 / 30^{o}C on paper germination was 16% while on a soil surface it was 54%. In incubator studies the base germination temperature for germination was around 6.0 to 6.3^{o}C, the optimum 27.6^{o}C and the maximum 42.1^{o}C (Wiese & Binning, 1987; Roman *et al.*, 1999). The base temperatures for root and shoot elongation were 4.5^{o}C and 7.5^{o}C respectively. The results were used to develop a model that described germination and seedling elongation.

In a study of seasonal effects on dormancy, seeds were buried 100 mm deep in soil shortly after collection and exhumed periodically in the dark to assess germination (Karssen, 1980/81). The seeds were most likely to germinate in spring and summer in the year after burial. Secondary dormancy was initiated in late-summer then alleviated again in late winter-early spring. In other studies, seeds were also exhumed at regular intervals after soil burial and their germination tested in the laboratory (Bouwmeester & Karssen, 1989). Germination levels were high in the light with nitrate present. Wetting and drying of the seed increased germination further in the presence of nitrate. In the absence of light there was no germination unless nitrate was present but even then it was still low. Over a 3-year period the tests showed only minor seasonal changes in germination levels (Bouwmeester & Karssen, 1993). Regardless of the season germination could occur when the field temperature was between 5 and 25^{o}C. In summer, germination may be inhibited as soil temperatures increase. The relief of dormancy begins in winter. In burial studies in the USA, freshly shed seeds maintained at alternating temperatures of 15/6, 20/10, 25/15, 30/15, 35/20^{o}C or at a constant 5^{o}C were exhumed at intervals and tested for germination at those same 6 temperatures (Baskin & Baskin, 1987). To fully after-ripen, seeds required exposure to low temperatures, however, a small percentage of seeds will germinate at higher temperatures if kept at a high temperature to after-ripen.

Fat-hen germinates mostly in spring but emergence continues through the summer up until August (Williams, 1963). There may be peaks of emergence in late April and August. In the USA, seedlings begin to emerge from mid-March and emergence is prolific through to the end of April (Ogg & Dawson, 1984). Emergence at a lower level continues through the season. Seeds produced by different cohorts may vary in dormancy status and response to environmental conditions and to management strategies (Mulugeta & Stoltenberg, 1998). However, after stratification in the field, percent emergence and mean emergence times were similar for seeds from all cohorts. In the field, seedling numbers usually represent less than 4% of the number of viable seeds present in the soil seedbank (Roberts & Ricketts, 1979). The highest percentages of seedlings followed cultivations in April and May. Seeds are thought to germinate more readily in high nitrate soils.

Seedling emergence from seed mixed into the top 20 mm of soil and stirred at monthly intervals took place from March to November with a peak in June (Chancellor, 1979). Seed sown in a 75 mm layer of soil in pots sunk in the field and stirred periodically, emerged from March to September with the main flush from May to July (Roberts, 1964). Seedling emergence in Scotland recorded in field plots dug at monthly intervals began in April and continued through until June/July with a peak in May (Lawson *et al.*, 1974). Brenchley & Warington (1930) found no real periodicity of germination when seed was sown in pans of field soil. Most seed germinated during first part of the experiment and few carried over to a later date suggesting that the seed may not have been typical. Seeds from 18 UK populations of fat-hen varied significantly in germination at warm and cool temperatures, and in seedling growth under standard conditions (Christal *et al.*, 1998). Second generation seed was used to minimise maternal effects. It was suggested that the differences were genetic in origin. In Sweden fat-hen is considered a summer annual (Håkansson, 1979). Seeds mixed with soil in the autumn, put in frames in the field, exhumed at intervals and put to germinate at alternating temperatures showed the seeds to have the lowest dormancy and greatest tendency to germinate from April to November. The main period of germination was from March to June. Some seedlings emerged in the autumn after sowing.

Under field conditions the number of emerged seedlings was positively related to the number of soil cultivations (Jensen, 1995). In the USA it was noted that seedling emergence was up to 30% greater where the soil had been compacted by tractor wheelings (Jurik & Zhang, 1999). In the field, 87-99% of fat-hen seedlings emerged from the surface 30 mm of clay and peat soils with the odd seedling from down to 60 mm (Chancellor, 1964). Seedling emergence declines with increasing depth of seed burial (Grundy *et al.,* 1996). When seeds were buried in discrete layers at 6, 19, 32, 57, 108 and 210 mm most seedlings emerged from the top 50 mm of soil. When the seeds were distributed through the soil profile down to the different depths, seedling emergence was spread further down the soil. However, there was a marked reduction in seedling emergence from seeds near the soil surface. Seed sown on clay soils with different clod sizes emerged most successfully from relatively fine soils and less well from coarse surfaces but fat-hen was not particularly sensitive to soil roughness (Harper *et al.*, 1965). Uptake of water by the seeds depends on them making good contact with the soil surface. Cultivation increases seedling emergence, often by bringing seeds into the upper soil layers. However, seedling emergence was less in untilled than in tilled soil even when seeds were maintained at the same depth (Mohler & Galford, 1997).

Fat-hen has a very plastic response to changes in the environment (Williams, 1963). On poor soils it is small and weedy, on rich soils it grows up to 2.89 m tall and very robust. Plants that emerge earlier in the year tend to be larger and leafier that those that appear later. Fat-hen has a great capacity for nutrient uptake because the branched roots have a rapid growth rate (Qasem, 1993). They are well distributed through the superficial 0-10 cm soil layer and at depths of 40-70 cm. Fat-hen shows a distinct morphological plasticity in response to plant density (Röhrig & Stützel, 2001a). A model has been developed that is able to reproduce the variation in stem elongation found in field studies. Dry matter production and resource allocation have also been quantified using simple models (Röhrig & Stützel, 2001b).

Fat-hen is a C_3 plant in terms of carbon fixation during photosynthesis (Baskin & Baskin, 1978). It shows increased rates of net photosynthesis, leaf area development, dry weight accumulation and vertical growth to elevated levels of CO^2 (Houghton, 1996). Fat-hen is killed by frost, and seedlings that emerge in autumn rarely survive the winter. Late spring frosts can affect seedling emergence early in the year.

In petri-dish tests, there was evidence that the decaying leaves of fat-hen had an inhibitory effect on crop seed germination (Goel *et al*., 1994).

Persistence and spread

Thompson *et al.* (1993) suggest that based on seed characters, fat-hen seed should persist for longer than 5 years in soil. Seeds are dormant when ripe and can remain viable in soil for up to 40 years (Williams, 1963). Seed buried in mineral soil at 13, 26 or 39 cm depth and left undisturbed retained 32, 22 and 15% viability respectively after 20 years (Lewis, 1973). Seed buried in a peat soil at 26 cm for 20 years retained only 6% viability. Seed buried in mineral soil gave 65% germination after 20 years (Crocker, 1938). In Duvel's burial experiment, seed buried at 10, 55 and 105 cm gave 39, 37 and 62% respectively after 10 years and 0, 7 and 9% after 39 years (Toole, 1946; Goss, 1924). Seed buried in soil in subarctic conditions had 49, 17 and 4% viability after 2.7, 6.7 and 9.7 years respectively (Conn & Deck, 1995). Seed stored under granary conditions was not viable after 20 years. Seed longevity in dry storage is 8-10 years and in the soil is 5-6 years (Guyot *et al.*, 1962). Dry-stored seed gave 65% germination after 1 year and 47 to 74% after 5 years while seed buried in soil gave 60% germination after 5 years (Kjaer, 1940). Seed kept in dry storage gave 23% germination after 4 years (Comes *et al.*, 1978). Apparently-viable seed has been extracted from the adobe walls of buildings in Mexico and the USA estimated to be 143 years old (Spira & Wagner, 1983). Seeds recovered from excavations and dated at 20, 30, 50, 80, 150, 300 and 600 years old are reported to have germinated (Ødum, 1974).

The decline of seeds broadcast onto the soil surface and then ploughed to 20 cm was followed over a 6-year period of cropping with winter or spring wheat (Lutman *et al.*, 2002). The trial was made on a clay and on a silty loam soil. Every effort was made to prevent further seed return to the soil. Fat-hen had a mean annual decline rate of 28% and an estimated time to 95% decline of 6-20 years. Seedbank decline studied in a succession of autumn-sown crops, winter wheat & winter OSR, in fields ploughed annually for 3-4 years with seed return prevented indicated that the mean annual decline of fat-hen was 52% (Lawson *et al.*, 1993). The time to 99% decline was calculated to be 6.3 years. The annual percent decline of seeds in cultivated soil was

31% (Popay *et al.,* 1994). In naturally occurring populations of fat-hen seed in undisturbed soil the annual loss was 22% (Roberts & Feast, 1973a). Seeds mixed with soil and left undisturbed had declined by 47% after 6 years but in cultivated soil the decline was 91% (Roberts & Feast, 1973b). Fat-hen seed sown in the field and followed over a 5-year period in winter wheat or spring barley showed an annual decline of around 40% (Barralis *et al.,* 1988). Emerged seedlings represented 8% of the seedbank.

Over several years, conventional moldboard ploughing and ridge tilling systems distributed fat-hen seeds evenly down the soil profile (Clements *et al.,* 1996). Chisel ploughing and no-till left two thirds of seeds in the top 50 mm of soil. Moldboard ploughed land had the largest seedbanks and this was reflected in fat-hen numbers in the emerged vegetation.. The depletion of seed buried at different depths for 19 months was greatest at or near the soil surface 0-25 mm (Murdoch & Roberts, 1982). Seed placed on the soil surface or buried at 25, 75 or 230 mm for 19 months showed losses of 68, 47, 39 and 36% respectively. Shallow soil disturbance did not increase the rate of germination from the 0-25 mm layer. It was estimated that after a seed-shedding event it would take 23 years to reduce seed populations back to the original level. In an extreme example, fat-hen seeds in the soil seedbank amounted to almost 3 cwt per acre (Roberts, 1966).

There is no obvious seed dispersal mechanism (Bassett & Crompton, 1978). Seedlings often occur in dense patches due to the seeds falling around the parent plant (Williams, 1963). Seed rain from plants that emerged after cultivation in early April extended from August to November (Leguizamón & Roberts, 1982). In this study, no fat-hen seeds were detected in initial soil samples but final seed numbers in soil were 52,140 per m^2 in the upper 10 cm layer of soil. A preliminary study in Sweden demonstrated that the number of fat-hen seeds left on the ground after combine harvesting an oat crop was over 17 times greater than when the crop was harvested with a binder, dried in shocks and then threshed (Åberg, 1956).

Fat-hen seed has occurred as a contaminant of crop seeds (Williams, 1963). It was a common impurity in commercial clover seed (Salisbury, 1961), especially alsike clover (Long, 1938), and in carrot seed (Bassett & Crompton, 1978). In a survey of grass and clover seed contamination in 1960-61, fat-hen seed was found in 4.2 and 5.1% of Italian ryegrass, 1.2 and 3.2% of cocksfoot 2.6 and 2.8% of meadow fescue samples tested of English and Danish origin respectively (Gooch, 1963). It was found in 12% and 43% of red clover seed samples of English and Canadian origin and 14 and 46% of white clover seed samples of English and Danish origin. In vegetable seed samples tested it was found in 39% of carrot, 25% of lettuce, 15% of celery and 1 to 18% of brassica seeds tested. In cereal seed samples tested in 1961-68 fat-hen was one of the frequent contaminants being found in up to 5.0% of rye, 2.8% of oats, 2.7% of barley and 0.9% of wheat samples tested (Tonkin, 1968). In a survey of weed seed contamination in cereal seed in drills ready for sowing on farm in spring 1970, it was found in 5% of samples (Tonkin & Phillipson, 1973). Most of these were from home saved seed. In the period 1978-1981, it was found in 4-6% of wheat and 6-11% of barley seed samples tested (Tonkin, 1982).

Low numbers of fat-hen seeds have been recovered from wormcasts on established grassland (McRill, 1974). Fat-hen seeds pass unharmed through the digestive systems of pigs and fowl but many are destroyed by passage through cattle (Williams, 1963). Nevertheless, apparently-viable seed has been found in samples of cow manure (Pleasant & Schlather K J, 1994). The seeds survived 1 month of anaerobic fermentation at 400 mm depth in manure but not at 1800 mm (Simpson & Jefferson, 1996). Viable seed has been found in cattle, horse and pig droppings (Salisbury, 1961). Seed was also found in sparrow droppings, and seedlings have been raised from the excreta of various birds. Germination appeared to be enhanced by passage through birds. Fat hen is often found growing on manure heaps. The seeds probably survive in the cooler outer layers of the heap. An application of manure significantly increased frequency of fat-hen and the number of viable fat-hen seeds in field soil (Borowiec *et al.*, 1974; Benoit & Cavers, 1998). Fat-hen was the most numerous seed to survive in fresh organic dairy farm manure but numbers were reduced by 90% after composting (Bilodeau *et al.*, 1999). Seed can survive ensilage (Williams, 1963). Seeds gave 34% germination after ensilage for 2 weeks but did not germinate after 4 weeks (Zimdahl, 1993). Most seeds were killed by ensiling for 8 weeks or a combination of ensilage and rumen digestion for 24 hours (Blackshaw & Rode, 1991). Rumen digestion alone left 40% of seeds still viable. In other studies, fat-hen seeds gave 58% germination after 47 hours digestion by cattle and 22% germination if then stored for 3 months in the manure (Zimdahl, 1993).

Seed has been found in irrigation water in the USA (Kelley & Bruns, 1975; Wilson, 1980). Seed submerged in water for up to 5 years gave a low level of germination for the first 9 months and odd seeds were still able to germinate for up to 4 years (Comes *et al.*, 1978).

Management

In field studies in Canada, there was no evidence that cropping sequence influenced the size of the seed population in soil (Benoit & Cavers, 1998). Because of its dormancy characteristics, the depletion of fat-hen seed is slow except at the soil surface (Murdoch & Roberts, 1982). This combined with the possible influx of new seeds precludes eradication and leaves containment as the management objective. Studies with soil clods of different sizes and hardness showed that seed germination was less and fewer seedlings emerged from larger clods when they were hard but the effect was noticeablely less in soft clods (Terpstra, 1986). Both a lack of light and the depth of incorporation in the clods were factors in limiting germination and successful emergence. Fat-hen emergence was 40% greater under moldboard and chisel ploughing systems than in no-till systems (Yenish *et al.*, 1992). Populations of fat-hen generally increased more in conventional tillage than no-till (Teasdale *et al.*, 1991). Seedling emergence is generally greater in tilled soil the effect of maize residues on emergence was not consistent (Buhler *et al.*, 1996). A mulch of rye (*Secale cereale*) had little effect on seed production (Mohler & Callaway, 1995). In sweet corn there was little difference in fat-hen seed production whether the crop was grown with conventional tillage or no-till. There was greater seed production in the absence of the crop.

The introduction of fat-hen seed with crop seed should be guarded against (Morse & Palmer, 1925). Vigorous and frequent hoeing of seedlings is effective in hot weather but large plants may need to be removed by hand (Long, 1938). Seeding must be prevented. In cereals, control is by surface cultivations with light harrows when crop plants are 2-3 inches high. Fat-hen populations may increase under root crops and with high fertilizer use (Williams, 1963). The relative growth rate of fat-hen increases with increased nitrogen levels and this is greatest at higher light levels (Bastiaans & Drenth, 1999). However, applications of ammonium nitrate fertilizer did not increase seedling emergence (Fawcett & Slife, 1978). In newly-sown grass, fat-hen seedlings do not survive cutting or trampling.

Based on studies in maize and soybeans in the Corn Belt of the USA it has been suggested that seedbank densities of 100 fat-hen seeds per m^2 would result in weed populations too low to affect crop yield (Forcella *et al.*, 1993). A seedbank density of 100 to 1,000 seeds per m^2 is likely to produce up to 400 weeds per m^2, a population that can be controlled adequately by mechanical means. Seedbank numbers above 1,000 per m^2 are unlikely to be controlled by mechanical means alone. Sowing date and the prevailing temperature and soil moisture level will affect the timing and extent of weed emergence.

Seedlings with 2-6 leaves are sensitive to flame weeding (Ascard, 1998). Fat-hen seed is susceptible to soil solarization. In addition, one novel way to use sunlight for direct weed control has been reported. It involves using a curved freshnel lens to concentrate sunlight into a narrow band at the soil surface, The wheeled device is pulled slowly along between crop rows to wither and burn off the inter-row weeds or kill exposed weed seeds. Under the full mid-day sun the mean soil surface temperatures achieved was 309°C with a 20 second exposure (Johnson *et al.*, 1990). The germination of fat-hen seed left on or near the soil surface was reduced to zero by this treatment. Seed is killed when heated at 95°C for 15 minutes in dry heat (Hopkins, 1936). Imbibed seeds in trays of moist soil held at 75 or 100°C for 12 hours lost viability but at 56°C the results were variable and seed viability was reduced by less than 50% after 16 days (Thompson *et al.*, 1997). Seeds held at 204 or 262°C for 7.5 and 5 minutes respectively were killed. In greenhouse tests of seedling susceptibility to ultraviolet-B radiation, fat-hen was a moderately sensitive species (Furness & Upadhyaya, 2002). Leaf area and biomass declined, shoot height was reduced and root biomass was also affected. In laboratory studies, naturally occurring fat-hen seeds in soil were killed by steaming at 65°C (Melander *et al.*, 2002). Preliminary studies of soil steaming in the field indicated that seeds of groundsel were controlled by treatment (Hansson & Svensson, 2004).

In laboratory tests, leachate from composted household waste decreased the germination of fat-hen seed (Ligneau & Watt, 1995). In pot tests, covering the seeds with up to 30 mm depth of compost reduced seedling emergence but so did covering with soil. In field studies, mulching the soil with residues of hairy vetch (*Vicia villosa*) and of rye (*Secale cereale*) reduced the emergence of fat-hen (Mohler & Teasdale, 1993). Weed emergence declined with increasing rate of residue, however, the natural rate of residue that remained after a cover crop was killed was insufficient for good weed control.

In greenhouse tests, corn gluten meal (CGM) applied as a surface and incorporated treatment to soil sown with fat-hen seed has been shown to reduce plant development (Bingaman & Christians, 1995). Application rates of 324, 649 and 973 g per m^2 reduced fat-hen survival by 82, 88 and 99% respectively. Shoot length was reduced by up to 100%. Corn gluten hydrolysate (CGH), a water soluble material derived from CGM, was found to be more active than CGM when applied to the surface of pots of soil sown with fat-hen seed (Liu & Christians, 1997). Wheat gluten meal (WGM) at 1 or 3 g.dm^{-2} dusted over seeds put to germinate on moist paper reduced germination by 0 and 64% respectively (Gough & Carlstrom, 1999).

In Canada, the mean rate of pre-dispersal seed predation in fat-hen growing in soyabeans was 4% and this was not affected by row spacing or tillage system (Nurse *et al.*, 2003). In a study of post-dispersal seed predation in spring barley the main predators were invertebrates, birds were not important predators at this time (Mauchline *et al.*, 2005). Seed predation was greatest earlier in the year when up to 70% of presented seeds were taken. Losses gradually declined over the summer and by late September few seeds were predated. The seeds are consumed by certain species of ground beetle (Tooley *et al.*, 1999). In Canada, ground dwelling invertebrates, particularly carabids, were the dominant seed predators (Cromar *et al.*, 1999; Swanton *et al.*, 1999). They were responsible for 80 to 90% of post dispersal seed losses that represented 20 to 30% of seeds shed. Small mammals and birds accounted for a further 10 to 20% of seeds. Seed density could be reduced by around 3% per day by post-dispersal predation. Tillage and the presence of crop residues were important in determining the level of predation. Plant residues covering the soil surface lower the temperature and reduce invertebrate activity.

Many insects are associated with fat-hen and several fungi and viruses can infect it (Williams, 1963; Bassett & Crompton, 1978). Applications of *Ascochyta caulina*, a fungus native in Europe, as a post emergence mycoherbicide has resulted in necrosis and mortality of fat-hen (Kempenaar *et al.*, 1996). The onset of necrosis began 2-3 days after treatment, and mortality occurred after 1-3 weeks. Up to 65% mortality could be achieved if plants remained wet for long enough after treatment but in dry conditions negligible deaths occurred. Sub-lethally diseased plants showed reduced growth and competitive ability. To be effective the fungus requires a high level of relative humidity for 20 hours after application (Stamatis *et al.*, 1999). In addition the target weed seedlings needs to be younger than the 4-leaf stage. Strains of the fungus with higher virulence and less dependence on a long dew period are being sought (Kempenaar & Scheepens, 1999). Major investment in research and development are required. Purified phytotoxins from the fungus also have a phytotoxic effect on fat-hen (Vurro *et al.*, 1999). Exposure to an arbuscular-mycorrhizal fungal inoculum has been shown to cause a 60% reduction in biomass in fat-hen, a non-host weed species (Jordan *et al.*, 2000). Infection by the sowbane mosaic virus (SoMV) reduces the viability of seeds by 15% (Horváth *et al.*, 2002).

Knowledge of the timing and extent of weed emergence following seedbed preparation should increase the efficacy of weed control strategies. A model has been developed that can predict the population dynamics of fat-hen in sugar beet (Freckleton & Watkinson, 1998). It is based on published data and is intended to be used to demonstrate the effect of changes in the level of crop and weed density, weed fecundity, seedling emergence and mortality, and seed persistence in the soil seedbank, and how this relates to weed management. Modelling emergence against meteorological data suggests that temperature is the dominant factor in determining an emergence event (Grundy *et al.*, 1999). Soil moisture is only important once the temperature requirement is met. A mechanistic seedling emergence model based solely on soil temperature has been developed for fat-hen (Harvey & Forcella, 1993). Modelling seed production by fat hen and linking this with a competition model provides an opportunity to simulate the effect of different management practices on crop yield and weed seed return (Grundy *et al.*, 2004).

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