Improving the efficacy of herbicides for the control of *Rumex obtusifolius* L. in Irish grassland using aspects of Integrated Weed Management

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By

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Declaration

I declare that thesis has not been previously submitted for a degree to this or any other institution and I further declare that the work in entirely my own work.

Tim O' Donovan
September 2022

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It is done!

Abstract

Docks are a troublesome weed of conventional grassland and can reduce grass dry matter (DM) production by up to 50%. Conventional farmers largely rely on herbicides to manage docks but often report disappointing results. With imminent EU legislation likely to restrict future herbicide use, there is an impetus to develop new dock management strategies. Three dock management experiments were conducted on a conventionally managed grassland farm (52°21N, 7°18W). Experiment I compared herbicides licensed for use in new leys (NLH) with herbicides licensed for use in established grassland (EGH). Experiment II examined the role of soil test Potassium (K) concentrations (Morgan's solution; Na acetate + acetic acid, pH 4.8; STK) on competitiveness of docks in grassland. Experiment III combined data from the two field studies to develop control thresholds of seedling docks in new leys. Dock numbers were measured over seven years (2010–2015) and herbage production over five years (2012–2016).

There was a 3.4-fold increase (due to clonal propagation) and strong correlation (R^2=0.9; $P<0.001$) between dock m^2 in 2013 and 2015. Each year (2013 to 2016), there were strong inverse relationships ($r > -0.776$; $P<0.001$) between dock and grass herbage production. NLH gave more ($P<0.001$) effective and enduring control than EGH, which varied in their effectiveness and showed recovery ($P<0.001$). STK influenced juvenile dock numbers ($P<0.05$). Lower STK values reduced ($P<0.01$) dock root and herbage production with an associated increase ($P<0.05$) in grass herbage production. Thus, STK levels can be manipulated as an alternative dock management strategy. Dock m^{-2} in 2010 accounted for 36% of the variation in the economic value of herbage produced from plots between 2012 and 2016. On this basis and considering the cost of NLH application, we recommend NLH's should be applied to avoid population densities >1.0 docks m^{-2} in new leys.

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Chapter 1 Introduction

1.1. General Introduction

Agriculture continues to be a key component of the Irish economy, making up 9.5% of national exports and employing 7.1% of the labour force (Anon, 2020). Grazed grass is the most important driver of Irish agriculture due its competitiveness as a feedstuff for ruminant animals (Finneran *et al*., 2010), our favourable climate for grass growth (O'Donovan *et al*., 2010) and the fact that 92% of utilisable agricultural area is grassland (Anon, 2020). Therefore, anything that enhances or curtails grass is of significant national interest.

Broad-leaved dock (*Rumex obtusifolius* L.) hereafter described as 'dock' or 'docks' is a ubiquitous weed of grasslands throughout Ireland (Courtney, 1985; Mitchell, 2001; Humphreys *et al*., 1997) and the UK (Hopkins, 1986). Numerous authors have stated the abundance of dock populations have increased with greater intensification of grassland management and particularly with intensive dairying (Hopkins and Peel, 1985) and the application of organic manures (Humphreys, *et al*., 1997). When dock population levels interfere with the general productivity of the sward (Oswald and Haggar, 1983; Doyle, 1982) and intake of grazing animals (Courtney and Johnston, 1978; Derrick *et al*., 1993), control measures need to be taken. Infestations of docks are difficult to control and extremely difficult to eliminate from the sward (Mitchell, 2001; Zaller, 2004; Creighton *et al.*, 2010). While docks are one of the most studied weeds in agriculture (Zaller, 2004; Bond *et al*., 2007), their management in intensively managed grassland is almost exclusively through the use of herbicides (Anon, 2019; Hopkins and Johnson, 2002). Recent innovations in non-herbicide control of docks such as targeting the roots (Van Evert *et al*., 2011., Latsch *et al*., 2017) or targeting the foliar growth (Stilmant *et al*., 2010, Hejcman *et al*., 2014, Van Evert *et al*., 2020) have not been widely adopted by intensive grassland farmers (Creighton *et al*., 2011). Such farmers require a rapid, robust, and economic method of dock control; thus, herbicides are still the most popular dock control option, despite their limitations such as impact on non-target organisms.

The laws pertaining to pesticide use and registration in Ireland and across the European Union are becoming increasingly restrictive. The Sustainable Use of Pesticides Directive (SI 155 of 2012) regulates how pesticides are used in Irish agriculture and encourages the use of Integrated Pest Management (IPM) to mitigate against the effects of reducing pesticide use (Anon, 2009). The European Communities (Plant Protection Products) Regulations 2012 (S.I. No. 159/2012) has changed the way pesticides are assessed and registered for use across the EU (Anon, 2012). The net result of this legislation is that there will be fewer new pesticides registered in the future and many of the currently registered pesticides will be removed from the market.

Furthermore, the EU's Farm to Fork and Biodiversity Strategies outline proposals that aim to further restrict pesticide use by 50% before 2030 (Anon, 2020). While the exact details of these proposals are not yet known, it is noteworthy that 96% of the pesticides applied onto Irish grassland are herbicides (Anon, 2019) and it is highly likely that their use will be restricted in the future. Previous surveys showed the single biggest reason that farmers apply herbicides onto grassland is for the control of docks (Anon, 2006), so it is imperative that improvements in herbicide efficiency and appropriate dock management techniques are researched and disseminated to farmers and their advisors.

1.2. Objectives

The primary objective of this study was to investigate the use of IPM, specifically Integrated Weed Management (IWM) techniques to improve the control of docks (thus increasing grassland productivity) in intensively managed grassland farming. One of the main drivers to complete this study was the fact that herbicides remain the primary control method for docks in intensive grassland but there are increasing environmental restrictions on their use. Achieving the objectives of this study should improve grassland productivity while at the same time help farmers comply with environmental legislative requirements.

The specific objectives of this study were:

- to investigate the long-term effectiveness of herbicides applied to seedling docks compared to herbicides applied to mature docks in an intensively managed grassland sward.

- to quantify the influence of potassium fertiliser on dock numbers, foliage growth and root characteristics over time and any effects on the grass sward.

- to develop benchmarks for dock management by monitoring key dock and grass metrics over a long timeframe (seven years) in an intensive grassland management scenario

1.3. Thesis structure

This thesis consists of six chapters. This introductory chapter (Chapter 1) has explained why this research was undertaken.

Chapter 2 is a literature review on aspects of dock biology, importance in grassland swards, control mechanisms and Integrated Pest Management.

Chapter 3 Effectiveness of dock (*Rumex obtusifolius* L.) control in new leys and established grassland following the application of herbicides.

Chapter 4 The influence of soil potassium status on the productivity of docks (*Rumex obtusifolius* L.) in intensively managed temperate grassland.

Chapter 5 Can seedling dock (*Rumex obtusifolius* L.) populations be used to predict long term grass production losses following re-seeding?

Chapter 6 summarises the main findings and discusses these results in relation to the objectives of this thesis.

Chapter 2 Literature Review

The objectives of this literature review are to provide a background on:

- Irish grassland and effects of weeds in grassland
- the occurrence and effects of docks in Irish grassland
- the biology of docks with reference to Irish grassland
- the current management options of docks in grassland
- integrated pest management, specifically integrated weed management

2.1. Role of Grass in Irish Agriculture

Production from ruminants (cattle, milk, and sheep) are the main drivers of Irish agriculture, combining to give 72.6% of Agricultural Gross Output at producer prices in 2013 (Anon, 2014). The largest constituent of these ruminants' diets is grazed grass (O' Donovan *et al*., 2010) which is not surprising, given that grazed grass is the lowest cost feed available for ruminants on Irish farms (Finneran *et al*., 2010). In terms of ruminant production economics, Dillon *et al*. (2005) demonstrated that the average cost of milk production is reduced by 1 cent per litre for a 2.5% increase in grazed grass in the cow's diet, while O' Riordan and O' Kiely (1996) demonstrated that increasing the proportion, quality and utilisation of grazed grass increases the carcass output of 24 month finishing steers from 553 to 970 kg ha^{-1} per year. In terms of winter fodder, grass silage is made on 87% of Irish farms with digestibility typically ranging between 630 and 700 g kg^{-1} dry matter (DM). The quality of grass either consumed as grazed grass or conserved as silage is an essential component of ruminant profitability (O' Donovan *et al*, 2010). In southern Ireland, under experimental conditions, the yield of grazed grass is consistently 15 t DM ha^{-1} and given genetic advances in grass varieties, has the potential to reach 18 t DM ha^{-1} (O' Donovan *et al*., 2010). At farm level, the measured yield of grazed grass is somewhat lower, averaging 11.2 t DM ha^{-1} ranging from 8.0 to 16.0 t DM ha^{-1} (Griffith *et al*., 2013). In the latter study, Griffith *et al.* (2013) did not give reasons as to why the farm yields of grass were lower than experimental yields but listed soil fertility, drainage, poaching and grazing management as items to address to improve grass production on farms. The production of quality grass is a key component of agricultural output in Ireland and anything that impinges on that production is a threat that must be managed.

2.2. Defining a weed species

There have been many definitions of the term 'weed' but most relay the sentiment of a plant that is a nuisance and, in some way, hinders or interferes with human activities (Naylor, 2002). The European Weed Society definition of a weed is 'any plant or vegetation, excluding fungi, interfering with the objectives or requirements of people'. Ecologically, Navas (1991) defined weeds as plants that cause damage by invading and replacing plants of agricultural or conservationist importance e.g., dense patches of creeping thistle (*Cirsium arvense* L.) have been shown to reduce plant biodiversity due to their dominance (Grekul and Bork, 2004). In economic terms, weeds are characterised as plants that reduce agricultural production and interfere with economic activities (Navas, 1991). Conceptually, whether a plant is a weed is a subjective decision based on the negative and positive attributes of the plant, however in agriculture, this is primarily based on lost production.

In summary, weeds can affect crops in many ways depending on the weed, its frequency, time and place of occurrence but also on the crop or marketable goods produced from that crop.

2.3. Effects of weeds in grassland

As stated above, in intensive agriculture, a plant becomes a weed when it causes damage and impacts on economic activities. In grassland, economic activities are primarily measured by animal performance, which is directly related to the amount, nutritive quality, and intake of grass (section 2.1). Weeds in grassland can cause economic loss in several ways: reducing edible dry matter yield and/or feed quality, directly affecting animal health through being toxic or physically injurious, contaminating animal products, and through the cost of their control. Weeds however can also exist at low levels in grassland with little or no economic consequences and plants often referred to as 'grassland weeds' are not always obvious since they may possess some forage value (Derrick *et al*., 1993; Harrington *et al*., 2006), even increase the overall dry matter yield of grassland (Courtney, 1985) and are an important source of nectar/pollen for insect species (Balfour and Ratnieks, 2022). These plants will therefore only become weeds when they reach a density that reduces productivity of the desired species (Doyle, 1984; Bourdot and Sackville, 2002). However, weeds can begin as innocuous and develop into a problem especially if they are adapted to their environment or by filling a niche in a monoculture. This can occur by increasing their numbers or increasing their own biomass production or a combination of both. A good body of research has been conducted on weeds in grassland (e.g., docks by Courtney 1985; creeping thistle by Grekul and Bork, 2004; ragwort (*Senecio jacobaea* L.), by Bourdot and Kelly, 1986) examining their effects and management strategies. Not surprisingly, the most comprehensive of this literature originates from New Zealand (Bourdot *et al*., 2007) where grassland production is of national importance.

Weeds primarily affect grassland production in four ways: competition, physical interference, and substitution, directly harming the animal and allelopathy, each of which will be covered in the following sections.

2.3.1. Competition

Weeds directly compete with the desired species (i.e., grass) for scarce resources (light, nutrients, water). Competition has been defined as ‘the tendency of neighbouring plants to utilise the same quantum of light, ion of mineral nutrient, molecule of water, or volume of space’ (Froud-Williams, 2002). However, competition is commutative or a ‘two-way street’, in that the crop can exert an important effect upon the weed, and this can be used to the farmers’ advantage when managing weeds. For example, maintaining a dense and vigorous sward is seen as the basis of weed management in grassland (Zaller, 2004). There are also critical periods or growth stages in the crop’s development, during which competition from weeds can exert a disproportionate influence on the crop’s yield. This is called the ‘critical period of competition’ and is the period during which the crop must be maintained weed-free to avoid irreversible damage through competition (Froud-Williams, 2002). An example of this is maize, where weeds exert their greatest yield reduction on the crop up to the 14-leaf stage and thereafter exert little influence (Hall *et al*., 1992). This phenomenon has been exploited in Denmark where cover crops are drilled between the rows of maize after this critical ‘weed-free’ period with little or no effect on the maize crop (Kristensen, 2019). There is very little reference to the critical period of competition in the literature regarding grassland weed species. It is possible that a grass sward could exert sufficient competition on a weed at critical times in the weed's lifecycle to the extent that it curtails future growth and/or reproduction and this is an area worthy of further research.

Docks have been shown to compete with grass for resources and this is expanded in section 2.8.

2.3.2. Physical interference and substitution

Weeds can also limit the quantities of grass consumed by the ruminant through physical interference by preventing the livestock from accessing the grass immediately surrounding the weed (Naylor, 2002). A classic example of this is creeping thistle which can reduce pasture production indirectly through impaired pasture utilisation (which in turn affects animal production) rather than by direct competition (Hartley and James, 1979). Creeping thistle affects sheep more than cattle and this 'under-grazing' can result in creeping thistle dominating sheep pastures. Similarly, spear thistle (*Cirsium vulgare* L.), through its prickly spines, also prevents sheep grazing the grass growing nearby (Hartley, 1983). Other weeds that deter animals from grazing close to the weed species include gorse (*Ulex europaeus* L.) and broom (*Cystis scoparius* L.). Docks have not been shown to prevent grazing and indeed have been shown to be grazed by ruminants (Courtney, 1985).

In a grazing scenario or under forage conservation systems, it is often the case that non-desired species may be inadvertently consumed by the grazing animal or conserved during forage making, thus reducing animal growth rates. Certain species such as docks, dandelion (*Taraxacum officinale* L.), buttercups (*Ranunculus* spp.) and rushes (*Juncus spp*.) are unpalatable or are of low nutritive value as compared to the desirable pasture species, thus taking space that could have been used to grow more nutritious species (Derrick *et al*., 1993). In his studies of docks in grassland, Courtney (1985) suggested that docks were about 60% as desirable as perennial ryegrass in terms of their impact on grass yields and lower digestibility.

2.3.3. Directly harming the animal and other effects

Some weeds in pastures can cause acute or chronic poisoning when consumed by livestock as they contain toxic compounds that can injure or kill animals even in small doses. Well known examples of this include poisonous plants such as hemlock (*Conium* *maculatum* L.) and ragwort (Cooper and Johnson, 1998). The consensus is that docks are not harmful to ruminants and may be beneficial in terms of supplying trace elements and reducing digestive upsets (Bond *et al*., 2007). In fact, there are potential benefits of having a low level of docks in a sward that was acknowledged by Courtney (1985) and Doyle (1984) in their assessment of docks as weeds in grassland. Wilman & Riley (1993) showed how broad-leaved dock was relatively high in P and K levels in the leaves, and particularly high in Mg and curled dock was shown to contain high levels of Zinc. As an aside, docks are known for their many beneficial properties in traditional medicine, and these claims has been tested and reviewed by Prakash Mishra (2018).

The presence of docks in silage slows down the wilting process and results in low production of fermentation acids (Hejduk and Dolezal, 2004). Waghorn and Jones (1989) found that a diet of 10% docks reduced bloat in stall fed cows. Other ways that pasture weeds affect production include reducing crop quality e.g., common chickweed (*Stellaria media* L.) reducing silage preservation characteristics, tainting animal products e.g., creeping buttercup tainting milk (Cooper and Johnson, 1998), effecting the marketable quality of the produce e.g., thistles can contaminate wool reducing its value (Naylor, 2002) and chickweed reducing the establishment of new leys (Brockman, 1985).

2.3.4. Allelopathy

Allelopathy is a term used to describe the mechanism by which plants release chemicals into the environment that can reduce the production of pasture plants in their surroundings. Naylor (2002) reasoned that allelopathy is of little consequence in Northern European conditions as allelopathic effects proven in the laboratory are not replicated in field experiments. However, there is also strong evidence to suggest that allelopathy needs to be considered as a possible contributing factor in how a species increases its dominance in an ecosystem (Wardle *et al*., 1998). Regarding docks, most of the evidence supporting an allelopathic effect is from laboratory experiments, but this may be since most field studies of docks were relatively short-term.

In laboratory and field studies, Carral *et al*. (1988) showed that decomposing dock leaves inhibit germination and root growth of dock seedlings. They supported their findings with a distribution study of species immediately surrounding mature docks growing in grassland. The authors found that the area affected (as measured by bare ground creation) was greatest nearer docks and positively correlated to the size of docks. They concluded that these allelopathic effects could contribute to the dominance of docks in a grassland ecosystem in conjunction with competition effects. Beres and Kazinczi (2000) showed that extracts from dock roots reduced the germination of maize, wheat and barley in pot experiments. Zaller (2006) showed that *Rumex obtusifolius* leaf extract significantly inhibited a range of pasture species in lab tests but was unable to repeat the results in analogous field tests. He demonstrated that dock leaf extract significantly inhibited germination of grass species such as cock's foot (*Dactyllis glomerata* L.) and smooth meadow grass (*Poa pratensis* L.) but had lesser effects on clover (*Trifolium repens*.) and dandelion germination. Interestingly, the dock leaf extract also significantly reduced germination of seedling docks. More recently, Anwar *et al*. (2018) found significant suppression of seedling growth of wheat, wild oats, maize and sunflower when they applied aqueous extract taken from curley dock (*Rumex dentatus L.*).

2.4. Key Aspects of Dock Biology in Grassland

Broad-leaved dock is a highly variable perennial species (Cavers and Harper, 1964) that occurs in a wide range of habitats, soil types and ecosystems (Bond *et al*., 2007). Docks belong to the family, Polygonanaceae, and are one of the most studied and important agricultural weeds worldwide (Zaller, 2004). Docks belong to the hemicryptophytes which are characterised by having buds located at the soil surface, protected by leaf and stem bases (Mauseth, 1998).

The biology, distribution, economic importance, and control of docks has been comprehensively reviewed by Cavers and Harper, (1964); Foster, (1989); Zaller, (2004) and most recently by Bond *et al*. (2007) and the pertinent aspects of dock biology to this study will be covered in this section of the literature review.

2.4.1. Distribution of docks

Docks have been described as a 'follower of man' (Cavers and Harper, 1964) due to their low abundance in native plant communities compared to their high frequency of occurrence in disturbed habitats such as field margins, roadsides, arable fields, and intensively managed grasslands (Zaller, 2004). In a survey of botanical composition of grasslands in England and Wales (Hopkins *et al*., 1988), stated that docks were most widespread in districts where there was a higher proportion of dairy farms. They found that fields with serious dock infestations were either cut for silage/hay or grazed by cattle, and docks were particularly abundant in fields that received over 100 kg N ha^{-1} and which had been reseeded during the previous 8 years. Docks are less likely to be found in areas subject to periodic flooding (Haggar, 1980) but experimentally, docks have been shown to be highly adaptive to flooding (Laan and Blom, 1989) and drought stress (Gilgen *et al*., 2010; Gilgen and Feller, 2013). Docks can be found in almost all soil types except on the most acid soils (Cavers and Harper, 1964). On a worldwide scale, docks are abundant in cool temperate climates, for example, in the UK (Turner *et al*., 2004; Hopkins, 1986); Northern Ireland (Courtney, 1985), Belgium (Stillmant, 2007); Japan (Hongo, 1989a) and New Zealand (Harrington *et al*., 2014). In Ireland, docks are considered native and widespread (Farragher, 1996) and do not appear to have any climatic limitation (Cavers and Harper, 1964).

2.4.2. Occurrence of docks in grassland

Considering the popularly held opinion that docks are prevalent in grassland, there is a lack of recently published information on the extent of their infestation levels at a national level. Most of the survey evidence on docks in grassland occurrence was conducted before 2000. Courtney (1972) listed docks as a problem on 11% of Northern Ireland grassland, surveyed in 1968. Haggar (1980) found, in a postal survey of UK grassland farmers, that 8% of grassland was infested with docks. The most common factors closely associated with the presence of docks were the application of slurry, farmyard manure and nitrogen. Peel and Hopkins (1980) surveyed 502 UK grassland farms, in the period 1974-1977, and found that 40% of farmers thought docks (R. obtusifolius and R. crispus combined) were a problem. Haggar *et al.* (1989) stated that docks were the most common perennial weed in grassland on UK dairy farms, especially young swards. Courtney (1985) found that docks comprised a greater proportion of silage swards compared to grazed swards. Humphreys *et al.* (1999) also found that docks were more commonly found in Irish silage fields compared to grazing fields when surveying 42 and 95 permanent grassland fields in 1993 and 1994 respectively. A survey of pesticide usage in Ireland in 2003 found that 38% of grassland farmers stated docks to be the primary reason why they applied herbicides, indicating that docks were a problem for a significant proportion of them (Anon, 2006). A more recent survey of 453 Irish dairy producers found that less than 1% of farmers stated weeds as a reason why they reseeded pasture (Creighton *et al*., 2011). Trade sources indicate that over 50% of selective herbicides purchased in Ireland in 2021 for use in grassland were for dock control (pers. comm.: Maughan, C).

Docks are considered a particular problem for organic farmers. Stilmant *et al*. (2007) surveyed organic farmers in southern Belgium, of which 40% considered that docks were a problem. A survey of 156 German organic farmers showed that 80% of the farms have problems with docks on 20% of their grassland area (Böhm and Finze, 2003). Turner, Bond and Davis (2004) surveyed 152 organic farmers in the UK and reported that over 60% responded that docks caused them the greatest concern. Dierauer and Stoppler-Zimmer, 1994 [cited in Zaller (2004)] identified that the fear of an infestation of docks was a major obstacle for farmers considering switching from conventional to organic farming in Central Europe. Conversely, Harrington *et al*. (2008) found that dock numbers did not increase when a conventional farm converted over to organic production, but this was in a mixed grassland arable situation.

Taking all the preceding published literature on docks in grassland, it is reasonable to conclude that docks are considered problematic by 40% of farmers but may only be infesting 10% of grassland. This is logical as farmers will be sensitive to lost production or areas where docks comprise a significant proportion of the herbage, causing them to act even though the 'problem' may be a low proportion of their overall farmed area.

2.4.3. Colonisation of docks in grassland

One of the fundamental aspects of managing docks in grassland is to identify and understand in what environments docks flourish and conversely what causes them to decline. Cavers and Harper (1964) concluded that the reasons why docks were a successful weed of agricultural grassland were their ability to flower many times each year, the production of large numbers of viable seed and the ability of this seed to germinate and quickly establish when conditions were favourable. However, as agricultural practices intensified in the 1970's and 1980's, several authors have concluded that the presence of docks is associated with the greater intensification of grassland management which is a function of defoliation and fertiliser applications (Haggar, 1980, Courtney, 1985; Jeangros and Nosberger, 1990). Hopkins *et al*. (1988) found that docks (*R. crispus and R. obtusifolius*) were most common in areas where there was a higher proportion of dairy farms and on farms with good soil fertility and where mowing was carried out. As shown in 2.4.2. silage fields are associated with increased dock incidence and biomass production whereas grazing fields are not. The reasons why docks do not flourish in grazing fields has been shown to be due to the frequent defoliations and trampling by animals, both of which are deleterious to tall species like docks (Hongo 1989b, Niggli *et al*., 1993). This has been proven experimentally; a silage regime (defoliation eight times over three seasons) did not reduce dock populations (Strnad *et al*., 2010) whereas a grazing regime (5-7 defoliations per season) controlled docks (Courtney, 1985; Stilmant *et al*., 2010). However, Van Evert *et al*. (2020) demonstrated that even intensive defoliation treatments (once per week for several months), while severely reducing dock biomass, does not eliminate them.

In contrast, docks have a much-reduced lifespan in unmanaged / abandoned grassland due primarily to underground competition from neighbouring grass species including *Elymus repens and Festuca rubra* (Martinkova *et al*., 2009). In this eight-year study, the authors observed that docks reduced in size in the year preceding mortality and that summer drought and root biomass of the grass species were correlated to the decline in dock density. To develop the findings of Martinkova *et al*. (2009) into a management strategy, Hann *et al*. (2012) investigated the effect of reducing management intensity as a control option for docks. In their three-year study, they found that well-established docks were not generally sensitive to management extensification but did show a general decline in numbers. It is likely that a longer-term experiment might have shown a greater reduction in final dock numbers. This is corroborated in farm surveys that found more traditional (or less intensive) farming practices such as hay making and grazing by sheep seem not to encourage docks (Cavers and Harper, 1967; Haggar, 1980 and Zaller, 2006).

In summary: intensive silage production (i.e., infrequent defoliation), the application of fertiliser nitrogen and organic manures and any activity that leads to a decrease in sward density have all been identified as reasons why docks become numerous in intensively managed grasslands (Courtney, 1973; Haggar, 1980; Peel and Hopkins, 1980; Humphreys *et al*., 1999). Control, but not elimination, of docks is achievable by frequent defoliation but in practice this is limited unless fields can be easily switched from silage making to grazing. Conversely, less intensive farming practices or leaving areas unmanaged are associated with lower dock populations but this area is not well researched.

2.4.4. Potassium and its role in dock biology

There is some disagreement in the literature about the role of potassium (K) and the occurrence of docks. Peel and Hopkins (1980) found that docks were common on soils deficient in potassium but rich in phosphorous. Humphreys *et al*. (1999) found that there were significant positive correlations between soil K concentrations and abundance of *R. obtusifolius* and *R. crispus*. This was based on field surveys but was also substantiated with pot experiments. Conversely, in a 2-year pot experiment, Van Eekeren *et al*. (2006) found that increasing the potassium status of the soil did not favour dock development in terms of numbers or biomass. More recently, Strnad *et al*. (2010) found that applications of fertiliser K had no effect on dock density (docks m^{-2}) or root regeneration capacity (post cutting the roots 5 cm under the soil surface) in a 3-year study. As part of the same series of experiments, Strnad *et al*. (2012) found that fertiliser K applications had little effect on biomass production, height of docks and leaf production. Hrdlickova *et al*. (2011) found a relationship between dock seed germination and the K status (K concentration in the leaf and stem tissue) of the mother plants. A recent New Zealand field-based study by Harrington *et al*. (2014) found a significant but weak correlation between docks m^{-2} and potassium but the authors concluded that this was not a good indicator of whether docks would thrive within a particular farm. Looking to other species with similar root structures as docks, Armstrong *et al*. (2000) showed that sugar beet root growth was dependent on soil K status pre-drilling as well as fertiliser K applications during the early growth stages of the crop. Tilman *et al*. (1999) found that dandelion populations were associated with elevated soil K soil concentrations.

Relating this to weed management principles, studies where species are competing for resources such as Tilman *et al*. (1999) are based on several aspects such as introducing a desired species that outcompetes the weed, increasing the number of desired species in the environment, thus out competing the weed species, or altering the environment to favour desired species over the weed species (e.g., altering the K fertiliser strategy to reduce dock competition). It is important that any alteration of the fertiliser strategy to manage weeds does not negatively impact on the grassland nutrition and DM production. The role of potassium in grassland nutrition is well researched (Ryan, 1977; Dampney, 1992; Keady and O' Kiely, 1998; Kayser and Isselstein, 2005; Lunnan *et al*. 2017) and integrated into agronomic advice (Wall and Plunkett, 2020).

Soil fertility has been associated with the population dynamics of docks. Most of the published work has been looking at aspects of nitrogen fertiliser, particularly the growth and longevity of docks in grassland (Courtney, 1985 and Niggli *et al*. 1993). Hopkins and Johnson (2002) found that dock DM yield increased by 1.0-2.0 t DM ha^{-1} when nitrogen and potassium fertiliser was added but suggested that the fertilisation components responsible needed to be investigated further with a view to management of docks.

In summary, there is some evidence that both soil K status and fertiliser K applications are linked to dock growth, but the evidence is not conclusive, and the length of experiment may be important in determining if there is a clear link.

2.5. Lifecycle of docks in grassland

In section 2.4 it has been shown that management factors strongly influence the population dynamics of docks in grassland. To see how individual factors affect aspects of dock growth, recruitment, and survival, it is first important to understand the lifecycle of docks in grassland. There is a wide body of literature and reviews already completed on this subject such as Cavers and Harper (1964); Foster (1989); Zaller (2004) and most recently by Bond *et al*, (2007). To understand how a population of docks occurs and flourishes in an ecosystem, this review will look at the following aspects of the weed's biology:

- growth and survival
- seed production
- recruitment of docks from seed
- recruitment of dock from roots and shoots

2.5.1. Growth

Once the dock seedling is established, the dock plant follows a set pattern of development of the rosette phase, the elongation phase, and the inflorescence phase.

Seedling dock roots (> 50 days after emergence) can regenerate if decapitated (Bond *et al*., 2007). Docks overwinter as a rosette with small dark leaves and a stout rootstock. In spring new leaves develop rapidly and there is a vegetative phase of elongation. Flowering stems arise from the tip of a shoot and grow to 100 cm tall with well-defined branches. The dock crown is a short (~5 cm length) underground stem above a relatively large tap root which may extend to a depth of 1 to 1.5 m on some soils (Bond *et al*., 2007). Leaves and new shoots emanate from the crown or more exactly from meristematic tissue in the leaf axils. Confusion arises due to the similarities between the crown and root as both are similar in appearance as the crown can produce adventitious roots. Pino *et al*. (1995) showed how the dock root tissue is devoid of such meristematic tissue so cannot produce new shoots (see section 2.7.2 on clonal propagation).

2.5.2. Survival in grassland

Individual dock plants are thought to survive for at least 5 years but probably survive much longer (Cavers and Harper, 1964). Courtney (1985) showed that 40% of docks survived six full seasons under a simulated grazing regime (5-7 cuts per year) and more than 60% survived for six years under a silage regime (3-4 cuts per year). More recently Martinkova *et al.* (2009) recorded that 4% of individually marked docks survived eight years in unmanaged grassland which is considered a very challenging environment for docks to survive in. Zaller (2004) stated that mature docks could live for decades in a favourable environment.

It is generally understood that the primary means of reproduction of docks is by seed (Cavers and Harper, 1964) however, clonal growth in an established grass sward (section 2.7.2) and re-growth from root fragments (section 2.7.1) when rejuvenating pastures are also important methods for docks to at least maintain and possibly increase their numbers.

2.5.3. Seed production

There is a good body of research detailing seed production aspects of docks. In summary individual dock plants can produce up to 60,000 seeds per year and these seeds can remain viable for up to 60 years which can result in five million seeds per acre in the top 15cm of soil, but this figure is probably higher where there is a history of dock infestation (Bond *et al*. 2007).

Generally, docks do not flower in their first year after establishment but can do so and in the second year, inflorescence production can begin in May and can occur anytime until the first severe frost in autumn (Cavers and Harper, 1964). Large, mature docks can produce two sets of inflorescences and seed per annum, one in May/June and one in August/September (Bond *et al*., 2007). Various factors such as low nutrient status (Hrdlickova *et al*., 2011), beetle grazing (Bond *et al*., 2007) and cutting frequency (Stilmant *et al*., 2010) have all been shown to reduce dock seed production, however, these need to be practised over many years to have a meaningful impact on viable dock seeds contained in the soil seed bank. Hejcman *et al*. (2012) showed that seeds of curled docks (*R. crispus*) when grown in P or K deficient soils in pot experiments, produced P and K deficient seeds with reduced germination capacity, while Cideciyan and Malloch (1982) demonstrated that dock seed size is related to seedling germination and subsequent growth. Broad-leaved dock (*R. obtusifolius*) commonly interbreeds in Ireland with other *rumex* species such as Curled dock (*R. crispus*) and produces viable hybrids (Farragher, 1996); however, the seeds produced by the hybrid between *R. obtusifolius* X *R. crispus* are quite sterile with a low percentage of fertile seeds (Cavers and Harper, 1964).

Once dock seed is produced it has an arduous journey before it can develop into a mature plant. Firstly, Weaver and Cavers (1979) estimated that over 90% of dock seeds are naturally lost due to predation, decay etc while secondly, Hongo (1989a) and Humphreys *et al*. (1997) showed how difficult it was for docks seedlings to establish in gaps created in existing swards. So, the apparent practical importance of the dock seed bank only becomes an immediate cause of concern when establishing a new pasture, especially if that pasture had an infestation of docks prior to rejuvenation and to a somewhat lesser extent if opportunities (large gaps) present themselves in an established grass sward.

2.5.4. Seed dispersal

Dock seeds become viable quite soon after flowering and their germination capacity increases as the mother plant matures from 10% in June to 85% in August (Cavers and Harper, 1964, Humphreys *et al*., 1997). It is the conditions that the dock seed find themselves in after being shed from the mother plant that will determine if the seed germinates or remain dormant and this will be covered in more detail in section 2.6.1. Dock seeds are well adapted to be dispersed over large distances (i.e., carried in water or on animals etc) but seed generally falls close to its parent (Cavers and Harper, 1964). The following section will concentrate on how dock seeds spread in fodder conservation and highlight key insights that can reduce seed as a source of docks. Several detailed experiments have decomposed this situation into its component factors i.e., the survival and spread of dock seeds in conserved forage, animal digestive tracts and in organic manure storage systems.

Conserved Forage

Grass is conserved in Ireland in four main forms: pit silage, baled silage, haylage and hay (see figure 2.1 for silage area breakdown). There is a widely held belief amongst farmers that dock seeds are 'spread' in conserved fodder, despite research to the contrary. Humphreys *et al*. (1997) ensiled 9600 dock seeds for 100 days in grass silage, which ranged between 18.7% and 19.4% dry matter and pH between 3.9 and 4.1. This silage was typical for most silages in Ireland. Following germination tests, no dock seeds ensiled in this silage germinated. Humphreys *et al.* (1997) attributed the lack of dock seed viability to pH but said more research was needed to clarify this point. More recently, Van Eekeren *et al*. (2006) demonstrated that the viability of dock seeds ensiled in grass silages of different dry matter percentages showed a decline in vitality with time. Seed viability was lost after 6 weeks in silage with a dry matter of 23% whereas 30% of seeds were still viable after 8 weeks ensilage in a 34% dry matter silage, indicating pH (acidity) is the causal agent for dock seed viability decline in silages. The pH was not described in this experiment, however, as silage DM increases so too does silage pH. This occurs because metabolic water available for growth of lactic acid bacteria starts to become limiting as silage DM increases (Kung *et al*., 2018). This is certainly an area worthy of further research especially possible interactions between forage pH, moisture content and preservation time and the impact of this matrix on dock seed germination. It is also worth noting how prevalent docks are in silage fields (section 2.4.2) and that over 1.4 million ha of silage are preserved in Ireland each year (Figure 2.1). The characteristics of conserved grass in various studies in Ireland are outlined in Table 2.1.

Table 2.1. Characteristics of conserved grass in various studies in Ireland

	Dry Matter % (Range)	pH (Range)	Source
Pit Silage (n=20)	22 (Not available)	3.8 (Not available)	McEniry *et al.*, 2006
Bale Silage (n=360)	32.1 (12.6 – 65)	4.5 (3.8-7.6)	O' Brien *et al.*, 2007
Haylage	55-60	Not available	O' Kiely pers. comm.
Hay (n=78)	78.2 (74.0-82.1)	Not available	Sheehan *et al.*, 1967

Animal Digestive Tracts

It is generally accepted that dock seeds pass relatively unaffected through the digestive tracts of cattle and sheep (Bond *et al*., 2007). This was studied by Humphreys *et al*. (1997) where dock seeds were placed in muslin bags in the rumens of fistulated steers for 72 hours. This treatment significantly reduced the viability of dock seeds but up to 50% remained capable of germination after 72 h.

Organic manure

Courtney (1985) and Humphreys *et al*. (1997) both demonstrated that dock seeds remain viable when stored in slurry for 12 and 14 weeks, respectively. Zaller (2007) compared different composting methods of farmyard manure and their effects on dock seed germination. Traditional composting (temperatures up to 63^{0}C) killed all dock seeds after two months whereas it took four months to render all dock seeds dead when using lower temperature (38^{0}C) composting methods.

Taking a typical scenario where grass and dock seeds are ensiled for 20 weeks, followed by feeding to ruminants and storage in slurry for 12 weeks, it is likely that the resultant slurry will contain virtually no viable dock seeds. However, where grass and dock seeds are conserved at high dry matters (>35%) or where dock seeds are present as contaminants in animal feed, it is likely that the slurry will contain some level of viable dock seeds. Anecdotally, farmers strongly believe that slurry from silage is a major source of dock spread but this is unlikely to be the case in most situations in Ireland.

2.6. Recruitment of docks from seed

As shown in section 2.5.3, there can be ample supply of viable dock seeds in the soil, especially where docks are numerous, and their environment favours seed production. Docks are more vulnerable to control measures during the seedling stage of their lifecycle (Hongo, 1989a; Humphreys *et al*., 1997; Keary and Hatcher, 2004; Bond *et al*., 2007), thus this is a key aspect in designing management strategies to control docks.

The definitions of germination, emergence and establishment can cause confusion when discussing dock management strategies but are quite important to distinguish between them as sites suitable for germination may not provide the appropriate resources required for growth or development of the establishing seedling (Cavers and Harper, 1967; Hongo, 1989a; Panetta and Wardle, 1992).

- Germination is defined as the emergence of the radicle to a length of 1 mm beyond the seed coat and growth is mainly from seed reserves (Harper, 1977).
- Emergence is defined as the expansion of the coleoptiles above the soil surface while the seedling is still dependent on seed reserves.
- Establishment is defined as the stage at which the seedling has developed a root system and photosynthetic area and begins to acquire resources from its environment for growth and survival (Harper, 1977).

There has been a large and detailed number of experiments conducted on the biotic and environmental factors that influence dock seed germination (Zaller, 2004). Suffice to say, dock seeds are heterogenous in their germination requirements and have no one characteristic germination ‘trigger’. This is probably due to the spatial variation of how dock seeds are distributed on and throughout the soil surface and profile and thus dock seeds experience altered environmental ‘triggers’ compared to what they are exposed to in carefully conducted laboratory experiments. Nonetheless, the germination of dock seed is governed by specific conditions about which we can give general guidance and how they can be manipulated for control purposes.

2.6.1. Dormancy

Seed dormancy is defined as the mechanism(s) which prevents the germination of seed under unsuitable conditions (Harper, 1977). Should a dock seed freely germinate, it is at risk of germinating too deep (running out of seed reserves) and/or germinating at the wrong time (during winter with frost risk) and/or germinating in a hostile environment (not being able to compete in a dense sward). Dock seed dormancy has been shown experimentally to be affected by conditions the seed encountered on the mother plant, such as maturity period and nutrition (Humphreys *et al*., 1997, Hrdlickova *et al*., 2011) or conditions encountered by the seed after being shed from the mother plant such as light, temperature and water availability (Roberts and Totterdell, 1981, Totterdell and Roberts, 1979, Vincent and Cavers, 1978). Furthermore, dock seeds exhibit heterogeneity of their germination requirements (i.e., breaking of their dormancy requirements) in terms of light, temperature, nutrients thus improving their chances of survival.

2.6.2. Germination and emergence

In an intensively managed grassland sward, light is the key process that can be influenced by farmers to minimise dock seed germination as it appears to be the primary environmental signal that allows weed seeds to detect disturbances and openings in the canopy. The process of how light regulates seed germination is well understood and is termed the phytochrome system (McLaren and Smith, 1978; Batlla and Benech-Arnold, 2014). Green leaves which contain chlorophylls and carotenoids, absorb more blue and red light than far-red light. Direct sunlight has an energy ratio of red light to far-red light of 1.2, whereas this falls to 0.2 when passed through a leaf (Taylorson and Borthwick, 1969). Leaf filtered light prohibits germination in dock seeds. Exposing dock seeds to direct light (after being exposed to leaf filtered light) results in high germination levels. However, exposing the same dock seeds to leaf-filtered light again stops the germination process. Milberg (1997) quantified that the photon fluence response of docks (i.e., the minimum threshold for seed germination) was 500 mmol m^{-2}, significantly greater than other species tested, thus indicating that dock seed has a high light requirement thus remaining dormant at the base of a typical grass sward. A second consequence of a leaf canopy covering over dock seeds is that it reduces the diurnal temperature amplitudes at the soil surface, particularly a sudden shift to higher temperatures. These fluctuations in temperature were shown to be a significant germination trigger for docks in Belgian experiments (van Assche and Vanlerberghe, 1989).

When viewed in combination with the low establishment capacity of dock seedlings (Section 2.6.3), this evolutionary strategy ensures that dock seeds only germinate when there is little or no competition from already established (and thus comparatively more competitive) plants such as grass.

Temperature and seed burial depth also play a part in this process hence dock seeds experiencing lower temperatures, require increased direct light levels to break dormancy and dock seeds buried > 8 cm deep do not germinate (Benvenuti *et al*., 2001). Dock seedlings germinate throughout the year, although typically there are two large flushes in March/April and September/October (Weaver and Cavers, 1979). This seasonality of germination in docks was explained as these times of year had the greatest temperature fluctuations (van Assche and Vanlerberghe, 1989).

So, in terms of preventing seedling recruitment from dock seeds lying at or near the soil surface, the key control mechanism is to maintain a reasonably dense grass sward thus preventing the correct light 'trigger' reaching these dock seeds and preventing temperature fluctuations at the soil surface during spring and autumn. Mean temperatures and rainfall patterns in Ireland generally meet the germination needs of docks. This also explains why dock seed readily germinate during grassland establishment, even in areas where no adult dock plants were growing in the immediately preceding years (Cavers and Harper, 1964).

2.6.3. Establishment

Despite producing copious amounts of seed, docks find it difficult to establish in dense swards (Pino *et al*., 1995) and appear to have a low competitive ability as seedlings (Hongo 1989a, Humphreys *et al*., 1997). Some researchers have noted that dock seedlings were rarely observed to establish in dock free swards in longer term experiments (Courtney, 1985; Hopkins and Johnson, 2003). When Cavers and Harper (1964) tried to establish broad-leaved dock in widely varying habitats (such as shingle beach and poached areas of grass fields), they found that dock establishment from seeds was only possible where an open habitat existed, and that gap colonisation is an important means of dock establishment, and the size of the gap is important to both germination and survival.

Breaking the process of gap colonisation into its component parts is important for managing docks in grassland. Firstly, dock seedlings emerge at different times through the year, but time of emergence has little effect on survival (Pino *et al*., 1997). Survivorship has more to do with seedling age and size. In other experiments, where the existing vegetation had been dug in to represent disturbed patches, seed sowing density had no effect on emergence (Weaver and Cavers, 1979) but more seedlings survived where a larger area of soil was disturbed. Docks (and other grassland weeds) developing from seeds are more likely to appear in large rather than small gaps as competition from established species around the large gaps will take longer to impact on the central parts, thereby providing sufficient time for seedling colonisation to occur (Bullock *et al*., 1995; Rogers and Hartnett, 2001). Humphreys *et al*. (1997) also found that broad-leaved dock seeds germinated but failed to establish in artificial sward gaps created by a variety of methods. Transplants of broad-leaved dock actively competed with other herbage plants and were better adapted to long term survival than curled dock. However, less than 2% of month-old seedlings of broad-leaved dock transplanted into an old, reseeded grassland survived for up to 4 years (Hongo, 1989b). Edwards *et al*. (2005) found that seedling recruitment of docks was more dependent on seedling survival than seedling emergence in established pasture in New Zealand. Despite adding 1000 dock seeds m^{-2} to established pasture, less than 5% survived 21 months post sowing. Survival was enhanced by continuous grazing compared with rotational grazing. Another finding in this study was that the presence or not of a sward canopy over precision sown dock seeds reduced germination but had no effect on dock seedling survival for the 21 months of their study.

A critical part of the research question as to why docks rarely establish in sward gaps was explained by Jeangros and Nösberger (1990) who demonstrated that root competition was the most important aspect of the *Rumex*–grass interaction in terms of the seedlings. Interestingly, docks that are regenerating from root fragments are equally sensitive to ground competition (above and below) from neighbouring plants (Zaller, 2004).

When grassland is reseeded, the dock seedbank is the primary source of new plants and dock seedlings can readily germinate and establish with the immature grass and other species (Harrington *et al*., 2013). Experimentally, dock seed sown at the same time as perennial ryegrass seed (*Lolium perenne* L.) suffered competition from the grass (Keary and Hatcher, 2004) whilst varying the grass seedling rate (Seefeldt and Armstrong,

2000) or the addition of clover (Humphreys, 1995) or adding companion crops (Ringselle, 2019) all significantly reduced dock germination and establishment. However, when the dock seed was sown 21 or 42 days in advance of the grass (analogous to docks germinating in a later sown or uncompetitive grass sward), the dock seedlings were able to establish a leaf canopy (Keary and Hatcher, 2004). Both Hongo (1989a) and Kristalova *et al*. (2011) found significant reductions (40% and 78 % respectively) in over-winter survivorship of dock seedlings in their first winter. In newly sown grassland, dock seedling survival was enhanced by frequent cutting of the sward (Hongo, 1989a), again reducing the competitiveness of the grass sward.

In summary, docks are more likely to establish where gaps in the sward are large, and the competing vegetation has been supressed for a sufficient period to allow establishment. However, root competition from surrounding vegetation has a large part to play in preventing dock seedlings establishing in sward gaps, which needs to be considered when evaluating if animal and machinery threading are reasons for docks increasing in established swards. In newly established grass swards, docks are relatively poor competitors and slight increases in competition from the sown components can significantly reduce dock establishment.

2.7. Recruitment of docks from roots and shoots

As has been shown in the previous section, docks need conditions favourable for germination and establishment from seed. In a competitive environment e.g., intensively managed grassland where practises are designed to recoup maximum production from grass and legume species, how do dock populations survive and spread?

2.7.1. Dock recruitment from root fragments

The ability of dock `root' fragments (composed of underground stem and true root material) to regenerate and form new plants has been demonstrated by Cavers and Harper (1964) and Hongo (1989b). Various authors have shown conflicting results when trying to clarify the parts of the dock root that can give rise to new shoots, but it seems this is probably due to mis-identification of the various parts of the root structure (see section 2.5.1). In general, the further down the root and away from the root collar the fragment arises from, the less the ability to regenerate (Alshallash, 2020).

Vegetative reproduction can only occur where buds are already formed and is most likely due to meristematic tissues being concentrated in these buds (Pino *et al.*, 1995). Alshallash (2018) found that dock shoots emerged quicker from root fragments than from seeds and that the larger the root fragment (5 g weight compared to 2 g weight) increased the speed of the dock root emerging. Monaco and Cumbo (1972) measured the time it took for a dock seedling to develop the capacity to propagate vegetatively from a rootstock, which they found to be 51 days.

Root fragments are more likely to give rise to significant numbers of new dock ramets during cultivations associated with reseeding of grassland and this is a serious problem in organic farming (Pye, 2008; Ringselle, 2019). In conventional farming, the herbicide glyphosate is almost universally applied to desiccate the old grass sward (Creighton *et al*., 2011) which kills the dock rootstock, thus negating this as a major source of new dock ramets when reseeding. Of lesser importance than root fragments is where dock roots are damaged by livestock or machinery in situ in established grassland and the roots of large dock plants are split. This is especially the case where clusters of large mature docks are growing near each other.

2.7.2. Dock recruitment through clonal growth

Clonal growth is a common survival strategy of plants, especially in what are termed 'closed communities' i.e., a plant community that does not allow for further colonisation and all the available niches being occupied (Harper, 1977). Ecologists commonly classify plants based on the type of clonal growth forms they exhibit and the spatial arrangement of plant ramets. In terms of common species in grassland, PRG and docks are termed phalanx species (Pino *et al.*, 1995; Cheplick, 1997), while creeping bent (*Agrostis stolonifera* L.) is a guerrilla species (Dong *et al*., 1995). Some species can adapt to environmental conditions and show both forms of clonal growth e.g., wild rye (*L. secalinus*; Ye *et al*., 2006).

Mature docks can form dense areas consisting of multiple crowns with taproots especially in grassland. This growth pattern was shown to be a phalanx type of clonal growth by Pino *et al*. (1995). The strategy of a phalanx species is to remain in a relatively fixed position if possible and to colonise neighbouring areas as they dominate over neighbouring plants due to being able to use nutrients efficiently (Klimeš *et al*., 1993). Plants exhibiting such growth structure produce slowly growing ramets that are closely spaced together. The process of clonal propagation in docks can be summarised as follows: juvenile docks begin to create secondary taproots in their second flowering year (i.e., three years after initial establishment). The taproots increase in size and the underground organs begin to fragment (Pino *et al.*, 1995). Subsequently, 4 to 5-year-old docks can become heavily divided and secondary taproots turn into the main root system, which then produces further secondary taproots. Eventually a dense population from a single clone will occupy a large area (Hopkins and Johnson, 2003). Pino *et al.* (1995) proposed that clonal growth is the main method of dock regeneration and population expansion in closed communities (i.e., where seedling establishment is unlikely to occur).

Another form of clonal growth is guerrilla or spreading clonal strategy. This involves the relatively fast production of a loosely arranged group of more widely spaced ramets (Harper, 1977; Lovett-Doust, 1981; Schmid, 1985; Lenssen *et al.*, 2005). Guerrilla species often invade opportunistic spaces or spread from resource poor into resource rich areas.

2.8. Docks as weeds in grassland

Despite the commonly held view that docks are a prevalent weed in grassland, there is a lack of recently published survey evidence supporting this view (section 2.4.2). In a survey of Irish grassland farmers in 2003, farmers ranked docks as the primary reason they applied selective herbicides onto grassland (Anon, 2006). Unfortunately, this line of questioning was discontinued in subsequent pesticide surveys series of surveys (Anon, 2013 and Anon, 2019). However, one can infer from the type and quantity of herbicides used in Irish grassland that docks continue to be a primary reason why these herbicides are applied (see section 2.9.3).

2.8.1. Effects of docks on grassland herbage yields

Apart from this survey evidence indicating that grassland farmers consider docks worthwhile applying a herbicide onto, there is a comprehensive body of scientific evidence demonstrating that docks are a serious weed of grassland. Savory and Soper (1973) recorded an increase in grass yields after treating various dock densities with a herbicide. Oswald and Haggar (1983) showed that dock populations of between five and ten dock plants m^{-2} reduced grass yield. They also showed that the effects of docks were more pronounced from August onwards and that ground cover as opposed to numbers of docks was a better indicator of reduction of grass yields. In a comprehensive study over six years, Courtney (1985) compared pure stands of docks, pure stands of perennial ryegrass and both species combined across nitrogen fertiliser and cutting regimes. The pure stands of docks yielded 60% of the grass yield in a simulated silage (3-4 cuts/year) situation compared to only 25% of the grass yields in a simulated grazing (5-8 cuts/year). He determined that when less than 10 to 15% of the ground area was covered by dock foliage, there appeared to be little effect on grass yields. Above this threshold, for every 1% increase in dock cover, there is a corresponding reduction in grass yields by 1%. He also showed that docks were slightly less attractive to grazing cows than grass, with 59% of docks eaten compared with 74% of the grass. More recently Hopkins and Johnston (2002) also compared the effects of dock populations across fertiliser and cutting strategies. In their experiments, the dock component of the herbage (0.6% in year one and 3.9% in year two) was small due to the transplanted docks being immature. In a following experiment, Hopkins and Johnson (2003) applied herbicide treatments to relatively mature docks which were transplanted into an intensively managed grass sward. In untreated plots, the proportion of dock herbage progressively increased over the four years of the experiment until it reached approximately 50% of the total herbage DM production, effectively replacing grass-based herbage with dock herbage. The authors also noted that the dock herbage progressively decreased in digestibility during each season as the dock developed a woody stem. Hejduk and Dolezal (2004) found that docks in silage reduced the wilting process and the production of fermentation acids.

2.8.2. Effects of docks on grassland herbage digestibility

Several studies have been carried out examining the quality of dock as a feedstuff compared to other grassland species (Courtney and Johnston, 1978; Waghorn and Jones, 1989; Derrick *et al.*, 1993). Courtney and Johnston (1978) stated that the average in vivo and in vitro digestible dry matter percentage of dock foliage was 58.1% compared to 75.5% for perennial ryegrass. Based on this work, (Courtney, 1985) estimated that docks have feeding value of approximately 65% of PRG. Courtney and Johnston (1978) also reported that the digestibility of the dock foliage declined as the docks matured and the rate of decline was greater than that of the grasses examined in their studies. More recently, Hejduk and Dolezal (2004) found that silage made from dock foliage had lower dry matter content and crude protein content that that of a red clover silage. Wilman and Derrick (1994) demonstrated that there was low retention of nitrogen by sheep fed dock foliage indicating that the protein in dock foliage is not efficiently digested and absorbed by ruminants. Courtney and Johnston (1978) also found that the in vitro and in vivo digestibility of woody stems and inflorescences of mature dock plants to be only about 50% of that of associated perennial ryegrass.

All of the preceding experimental work above was conducted using either transplanted docks arising from seed and grown as plugs or seedlings raised from excised dock root sections and/or protected from livestock and farm machinery and /or was over relatively short time frames. This approach is necessary to be efficient with resources and allow for many treatments and populations.

2.9. Herbicide control of docks

Given the highly adapted nature of docks as a weed in grassland, most researchers examining the control of docks in grassland aim to control docks to an acceptable level by hindering the build-up of seeds and weakening the dock's ability to re-grow by removing or destroying above and below ground biomass (Zaller, 2004).

2.9.1. Economics of herbicidal weed control in grassland

The decision to spray with a herbicide is a complex one, depending on the objectives of the farmer but the overall objective of any control programme is to maximise profit rather than yield (Jones *et al*., 2000). Section 2.3 covered the impact of weeds in grassland and when aggregated, weeds are quite a significant cost in terms of lost output. The most recent review of weeds in temperate grasslands (New Zealand) was conducted by Bourdot *et al*. (2007). They concluded that the aggregate cost from grassland weeds was NZ$1.2 billion per annum while in the United States, DiTomasso (2000) estimated that weed infestations cause at least $2 billion in annual losses in pastureland.

The cost of control and expected financial gain are important factors in any decision to apply a herbicide. In a survey conducted by Toor and Stuck (1993), New Zealand farmers were found to base their decision to control weeds and pests on the cost of control and the availability of surplus funds. Since most herbicides cause some damage to pasture, any decision to spray must also take that productivity loss into account.

2.9.2. Threshold Level

In arriving at a decision to apply a herbicide, a common approach is to use an Economic Threshold Level (ETL). This is the weed density at which the cost of control equals the financial benefit derived from controlling the weeds in that same year (Cousens *et al.*, 1985). When the weed density exceeds the threshold level, the cost of herbicide application is less than the financial losses because of reduced production. The ETL concept is well used in arable cropping with comprehensive datasets available for the main arable weeds. Typically, such ETL's outline the number of weeds m^{-2} to cause a 5% yield loss and depending on the crop economics, an agronomist or farmer can make a quick decision to apply a herbicide. When added to information on the critical period of compensation (Section 2.3.1), this is quite a useful decision-making process (Naylor, 2002).

In grassland, ETL's are not widely used by farmers because of various limitations (Cousens, 1985). One problem with economic thresholds is that the competitive ability of pastures varies depending on soil fertility, grazing intensity and other environmental factors. In addition, the occurrence of multiple weed species in various combinations makes the concept of ETLs difficult to implement in grassland. Another problem with the use of thresholds in pastures is in measuring the economic benefits of controlling weeds. For the thresholds to make sense, any increase in herbage production because of herbicide treatment has to be utilised by the livestock before financial benefits can be realised (Haggar *et al*., 1989).

Moore *et al*. (1989) constructed a mathematical model for nodding thistle (*Carduus nutans* L.) in New Zealand grassland, where it is a problematic weed species. This model looked at the long-term economic implications of controlling nodding thistle in grazed pasture using the herbicide MCPB. The study found that it was beneficial in the long term to apply the herbicide in October (springtime in New Zealand) or whenever nodding thistle ground cover exceeded 2.5%. This work confirmed that timing and weed density are important considerations in constructing an economic threshold level. Doyle *et al*. (1984) constructed a model to allow the prediction of the effects various herbicide control strategies of docks in grassland. One of the findings was that additional information was needed on dock population dynamics and the factors that influence the susceptibility of docks to herbicides.

Besides an economic yield loss in the current season, other concerns may determine when weed control is justified. For example, weed densities might not be economic to control in one year but failure to act might lead to more adverse economic problems due to weeds building up through seed production in the following years (Doyle *et al.*, 1984). The large numbers of seeds that can be produced by a single plant requires the threshold concept to be extended to include potential future impacts of the current weed population. Farmers who therefore apply herbicides to low densities of weeds to prevent seed build up are trying to maximise the benefits of weed control over a longer timeframe as compared to those who want to maximise benefits in a single year (Doyle *et al.*, 1984).

2.9.3. Herbicide control

There is almost no recent (within 20 years) scientific literature examining the control of docks using herbicides. This appears quite extraordinary considering over 50% of grassland herbicides are sold for that purpose for controlling dock populations in Ireland each year (pers. comm.: Maughan, C) and 100% of pesticides applied onto Irish grassland are herbicides (Anon, 2019). There are even less references concerned with herbicide control for seedling docks in the literature (except Blair and Holroyd, 1973) even though it is commonly inferred that dock seedlings are easily killed by herbicides. Most experiments reported in the literature concerning herbicidal control of docks were conducted on mature docks that were either transplanted or assessed using very small plots (1 to 2 m^{-2}) or assessed under a short time frame (less than two years). The consensus of surveys of farmer opinion and of older scientific experiments concerned with controlling mature docks in grassland was that herbicides controlled docks but needed repeat applications (Savory and Soper, 1973; Haggar, 1980). Using more modern herbicides, one would expect dock control to be significantly improved in recent years but that does not agree with the views of farmers (Creighton *et al*., 2010).

2.9.3.1. Herbicide control of docks – experiments

The use of herbicides for dock control is well established and well researched but more so before 2000. Almost as soon as selective herbicides such as 2,4-D, MCPA, asulam and chlorsulfuron were being discovered, researchers had begun to conduct experiments on their efficacy at controlling docks (Gordon, 1955; Brock, 1972; Oswald *et al*., 1982). Blair and Holroyd (1973) carried out a comprehensive range of experiments on the effectiveness of dock herbicides available at that time. They looked at the long-term control of individual docks in managed micro plots. After the experimental treatments were applied to each plot, paraquat was applied annually to prevent new dock seedlings or other species establishing in the micro plot. The authors clearly showed that significant long term (up to two years) control of docks can be achieved when herbicides are applied before a taproot is formed. However, once the dock taproot became established, permanent control was limited to a small number of treatments, and all treatments exhibited some dock re-growth.

Good control of docks and an increase in grass yields were achieved by the herbicide Asulam in the experiments of Savory and Soper (1973) and Oswald and Haggar (1976). In both experiments, overall herbage yield remained the same after the docks were controlled but the proportion of grass in the sward increased significantly. However, re-growth by the docks was evident within 18 months after application with a recommendation that a repeat herbicide application was required for longer term control. Savory and Soper (1973) concluded that the long-term success of the herbicide treatments was dependant on the management of the sward (post-herbicide application) and the ability of the grasses to exploit the spaces left vacant by the removal of the docks. Oswald and Haggar (1976) suggested that further work was required to closely examine the recovery of docks (post herbicide applications) to determine if such re-growth emanated from seedlings or rootstocks. Courtney (1985) summarised several experiments using mecoprop/dicamba mixes to control docks. The trend was for the herbicide to increase the yield of herbage, other than dock, where dock ground cover was >20% under a grazing system and where dock ground cover was 25-30% under a silage system. Courtney (1985) also identified areas of further research looking at factors that influence herbicide efficacy, reaction of the sward to herbicides including the competition aspects between sward species post herbicide application and the effects this has on control of docks. Mitchell (2001) assessed a wide range of herbicides on mature docks in a well-established sward, including claimed clover safe options (amidosulfuron; trade name Eagle, Bayer Cropscience). One year after treatment, field assessments indicated a general reduction in dock control in all cases but the fluroxypyr/triclopyr and amidosulfuron treatments gave better dock control than the dicamba based product. There was no visual effect on the grass component of the sward, but clover was eliminated in the fluroxypyr/triclopyr and dicamba plots. Mitchell (2001) concluded that dock control was acceptable in all treatments, one year after herbicide application when compared to the untreated control but dock re-growth was evident.

Hopkins and Johnson (2003) tested Pastor (Dow AgroSciences), a formulation containing clorpyralid, floroxypyr and triclopyr, on ‘medium’ (11.9 dock ramets m^{-2}) and ‘high’ (16.2 dock ramets m^{-2}) densities of three to four-year-old transplanted docks. They found that this herbicide significantly reduced all dock densities but did require a repeat application where some re-growth occurred a year after herbicide application. The same authors also found that grass herbage DM production increased by 3 t DM ha^{-1} $year^{-1}$ by effectively replacing the dock herbage controlled by the herbicide. More recent Irish herbicide dock control experiments also show very good short-term control of the dock population but with some level of dock foliage regeneration occurring within 12 months of application (Creighton *et al.*, 2010). These herbicide experiments did not measure the longer-term benefits of the herbicide such as quantifying the re-growth capacity of the docks or any effects the docks may have had on the grass species in the sward. In a related experiment, Power *et al.* (2013), demonstrated that non-target species diversity was greatly reduced by blanket herbicide applications (i.e., applied to the whole area). This was measured by a composite species index. They found that a novel automated herbicide application technique (a tractor mounted camera to identify and apply herbicide to docks) had less effects on non-target species diversity but failed to control the docks.

In a reseeding scenario, many herbicides are registered for use once the grass plant has 2-3 leaves (Anon 2021b). In mixed grass/clover swards the choice of herbicides is greatly reduced as many herbicides are not selective between broad-leaved weeds and clover as both are dicots (Mitchell, 2001). Combining the facts that docks are easily controlled as seedlings and that a competitive grass sward will greatly reduce the number of new seedlings establishing in the sward (Section 2.6.3) is an area worthy of investigation.

2.9.3.2. Future herbicide research into dock control

One possible reason for the poor long-term control of dock populations is that farmers use herbicides as a quick ready-made solution with little regard to other control techniques such as cultural methods or by exploiting weaknesses in the biology of the dock plant. There is also benefit from improving application efficiency of herbicides, which has benefits such as protecting non-target organisms as well as reducing pesticide loading in the environment (Smith and Thomson, 2003; Royston *et al*., 2006; Moyo, 2008). Combellack (1989) identified strategies to improve herbicide use efficiency such as timing of application, targeting herbicides to weeds, use of effective formulations and threshold levels. He estimated herbicide savings of up to 75% by spraying weeds only where they occur. This approach was tested by Creighton *et al.* (2010) using a sprayer mounted camera which gave the same control of dock densities as standard boom sprayer herbicide applications although with much reduced herbicide use. However, the authors concluded that more research was needed to improve the technique in terms of the weed identification aspect and herbicide volume required. Camera guided boom sprayers such as WeedSeeker® 2 are becoming more common on arable farms in Australia and North America but have not been widely used in grassland (Roberts, 2021). The patchy distribution and slow spreading nature of weeds lends itself to spot spraying and very significant reductions in herbicide volumes (up to 90%). However, the initial investment of such systems is not justified, except on the largest of grassland farms. It is much more likely grassland farmers will employ a contract service to provide the implementation of such technology (Anon, 2022b).

2.9.4. Herbicides for dock control

The range of herbicides available for grassland weed control in Ireland is comprehensive with 66 registered selective herbicides for established grassland and 22 selective herbicides registered for new leys (Anon, 2021b). Most of these herbicides offer control of docks to some degree. A survey of grassland establishment practices on dairy farms in southern Ireland revealed that only 53% of farmers applied a post-emergence herbicide routinely as part of their grassland establishment procedure even though 89% of the same survey population had applied glyphosate to desiccate the old sward (Creighton *et al*., 2011). A detailed analysis of why so many farmers did not apply a post-emergence herbicide is not available; however, it is reasonable to assume that late sowing date accounted for a proportion. However, a lack of monitoring of the weed population in the resown swards and a lack of knowledge regarding the benefits that can be accrued from an appropriate post-emergence spray, could also be reasonably assumed to be reasons why a proportion of farmers did not apply a post-emergence herbicide to their new leys (pers. comm.: Maughan, C).

2.9.5. Legislative regulations of pesticides in Agriculture

There are many facets to how pesticides are regulated by law in Ireland and the EU ranging from their initial registration, to how they can be used and ultimately to what residues are acceptable to remain in the environment. The following sections detail this with reference to grassland herbicides that are active on docks.

2.9.5.1. Herbicide registration

An important consideration in the evaluation of herbicide experiments or farm level surveys is the whole process of herbicide evaluation and registration in the EU. As mentioned in chapter 1, this process is extremely well regulated and recently updated. In summary, all herbicides for sale in the EU must undergo a standard evaluation process, regulated by the EPPO (The European and Mediterranean Plant Protection Organization) which is responsible for cooperation and harmonisation in plant protection within the European and Mediterranean region (EPPO, 2021).

Firstly, to claim ‘control’ of a named weed species on a product label, the herbicide must satisfy the EU competent authorities (DAFM for Ireland) that it will reduce weed number or % ground cover of the listed weed species by at least 80% relative to an untreated area when applied in accordance with the label (EPPO, 2009). Secondly, for perennial species (such as docks), if the herbicide label claims, ‘long term control’, then the herbicide registration trials must include an assessment of herbicide efficacy in the year following application (EPPO, 2009). So, a herbicide that claims ‘control’ of docks is not assessed in the second year after application but must only reduce dock density or % ground cover by at least 80% in the year of application. A cursory look at some modern grassland herbicides and their claims is in Table 2.2.

Table 2.2 Selection of grassland herbicides and label claims with respect to dock control

Trade name (Marketing Company)	Registered for use on grassland in Ireland 2022	Active ingredient	Label claim regards dock or *rumex spp.*
Asulox (Bayer CropScience Ltd)	No (withdrawn in 2014)	400 g/L (33.6% w/w) of the sodium salt of asulam	*For light or recently established infestations, one application of Asulox should be sufficient. For heavy or long-established infestations two applications, at least ten months apart, are recommended. Always carry out any second treatment in the season following the initial application.*
Doxstar Pro (Corteva agriscience)	Yes	Fluroxypyr 150 g/l Triclopyr150 g/l	*Doxstar Pro is a foliar acting herbicide for the control of broad-leaved and curled dock in established grassland.* *On large well-established docks and where there is a reservoir of seed in the soil, a further control programme in the following year may be required.*
Eagle (Bayer CropScience Ltd)	Yes	75% w/w amidosulfuron	*For use only as an agricultural herbicide…and for the control of docks in grassland* *When docks are well established or where there is a large reservoir of seed in the soil a programme of treatments may be required for long term control*

2.9.5.2. Herbicide use legislation

The laws pertaining to pesticide use and registration in Ireland and across the European Union are becoming increasingly restrictive. The Sustainable Use of Pesticides Directive (SI 155 of 2012) regulates how pesticides are used in Irish agriculture and encourages the use of Integrated Pest Management (IPM) to mitigate against the effects of reducing pesticide use (Anon, 2009). This law was enacted in 2009 and has four main pillars that regulate: the user of the pesticide, the equipment applying the pesticide, the agronomist giving advice in a professional capacity on pesticides and the seller of pesticides. All four impact on grassland herbicide use and are covered in detail in the legislation. In summary, users, sellers and agronomists of agricultural pesticides must be trained to a defined standard and approved to operate within their sphere of pesticide use and undertake continuous professional development. Also, equipment used to apply pesticides must be regularly tested by Government appointed testers.

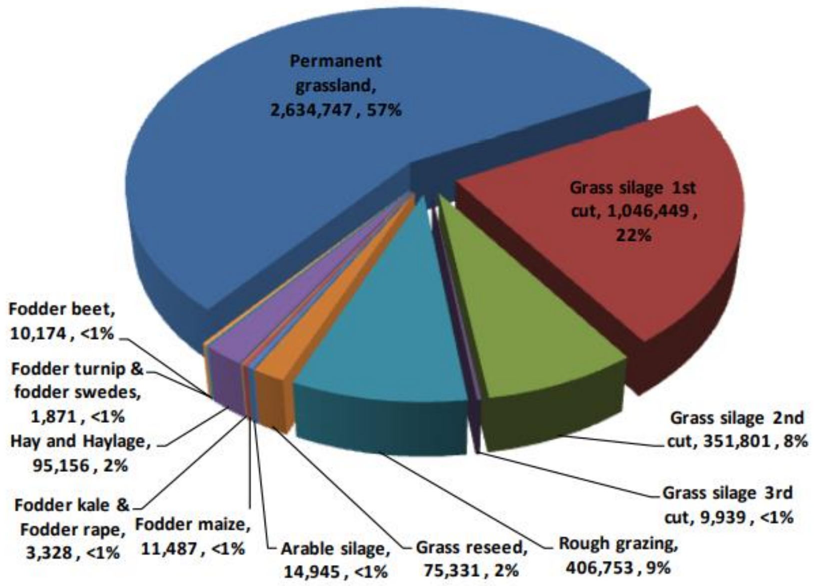
2.9.5.3. Marketing of herbicide legislation

Regarding the marketing of pesticides, the European Communities (Plant Protection Products) Regulations 2012 (S.I. No. 159/2012) has changed the way pesticides are assessed and registered for use across the EU (Anon, 2012). Specifically, the legislation is moving more from a risk-based assessment of the herbicide to a hazard-based assessment. A parallel example of this is that alcohol is classified as a hazardous chemical to human health. However, when alcohol is consumed in moderation etc, it is considered a low risk to human health. If alcohol was a new herbicide, it would be unlikely to be allowed to market as it is a hazardous chemical, with no allowance made for risk reduction. The net result of this legislation is that there will be fewer new pesticides registered in the future and many of the currently registered pesticides will be removed from the market.

2.9.5.4. Herbicide Usage Reports

Under the SUD legislation, competent authorities in each EU member state are obliged to survey pesticide (incl. herbicide) usage (Anon, 2012). Overall, 10.2% of the entire Irish grassland area (4,620,178 ha) received a herbicide application in 2017, representing quite a significant area treated (469,930 ha; Figure 2.1). What is noteworthy is that herbicides comprised 100% of the pesticides applied onto Irish grassland in 2017 (Anon, 2019). However, some duplication of treatment areas can occur in the same year such as reseeds receiving glyphosate and a post reseeding herbicide, which were not distinguished in the survey. In 2003, the Pesticide Usage survey in Ireland found that 38% of herbicides were applied for control of docks, 19% for rushes, 10% thistles and 2% nettles (Anon, 2006).

Figure 2.1 Areas of individual grassland and fodder crops grown in Ireland (ha), 2017



Anon (2019)

Note: Permanent grassland refers to grassland that was grazed only and not conserved for fodder purposes (pers. comm.: Quirke, J).

2.9.5.5. Environmental legislation of herbicides

Irish Water are the competent authority in Ireland responsible for the monitoring of pesticides in public drinking water supplies to determine if relevant standards are met (Anon, 2022a). The level of pesticides in water is regulated by the EU Drinking Water Directive (DWD; 98/83/EC) and its Irish statue (SI No. 122/2014). The parametric values for pesticides in the drinking water regulations are 0.5 µg/l for total pesticides and 0.1 µg/l for individual pesticides and their relevant metabolites, degradation and reaction products (Anon, 2022a).

The World Health Organisation sets guideline limit values for individual pesticides in drinking water summarised below and are significantly higher than the DWD limits. While the WHO values do not have a regulatory standing, they are valuable in the determination of any potential risk to human health presented by a breach of the EU DWD regulatory limits (Anon, 2022a).

Table 2.3 WHO Pesticide Limits (selected) in Drinking Water

Pesticide	Description	WHO guideline value
MCPA	Herbicide, most commonly used in Ireland to control rushes in pastureland, also in amateur-use garden herbicides.	2 µg/l
Mecoprop	Widely used general herbicide, also in amateur use garden herbicides.	10 µg/l

From 2010 to 2012, there was an increase in the detection level of the phenoxy herbicides (mainly MCPA) in Irish drinking water samples (Hayes *et al*., 2012). This ‘background’ level of pesticides being found in drinking water supplies are beginning to cause concern with a new cross-governmental working group being formed to promote good practice when using herbicides in grassland. More recently, the EPA have reported that the number and level of pesticide exceedances has decreased and attributed this improvement to work conducted by this cross-governmental group which promoted best practise using pesticides (Anon, 2022a). The most detected pesticide in drinking water supplies since 2010 has been the herbicide, MCPA. This herbicide is most used for selective rush control in grassland and for amateur garden use. Other herbicides which have been detected include: 2,4-D, Glyphosate, Triclopyr, Mecoprop and Fluroxypyr, all of which were detected at significantly lower frequencies than MCPA. All of these are herbicides commonly used in Irish grassland (Anon, 2021b).

2.9.5.6. Summary of herbicide legislation

As seen in the previous sections, there is increasingly tightening surrounding herbicide use. Furthermore, the EU’s Farm to Fork and Biodiversity Strategies outline proposals that aim to further restrict pesticide use by 50% before 2030 (Anon, 2020a). While the exact details of these proposals are not yet known, it is noteworthy that 96% of the pesticides applied onto Irish grassland are herbicides (Anon, 2019) and it is highly likely that their use will be restricted in the future. Previous surveys showed the single biggest reason that farmers apply herbicides onto grassland is for the control of docks (Anon, 2006), so it is imperative that improvements in herbicide efficiency and appropriate dock management techniques are researched and disseminated to farmers and their advisors.

2.10. Non-herbicide control of docks

As stated in section 2.9.3.2, dock control by herbicides requires repeated applications. Where there are requirements to use management options to avoid or reduce herbicides, there are many non-herbicide options available, which have been reviewed by Zaller (2004).

2.10.1. Defoliation strategies

A popular control method for docks and many perennial grassland weeds is defoliation either by cutting, animal grazing or pulling by hand (Kluth *et al*., 2003, Zaller, 2004, Bond *et al*., 2007; Poetsch and Griesebner, 2007; Rinella and Hileman, 2009; Nkurunzia and Streibig, 2011). Essentially, docks try to maintain a root to shoot ratio of 70:30 and cutting dock foliage encourages the dock to replenish and grow its foliage using root carbohydrate reserves as it tries to maintain this ratio (Zaller, 2004; Stilmant *et al.,* 2010; Hujerova *et al*., 2013). Courtney (1985) presented very clear evidence that the effects of docks on grass herbage DM production were significantly reduced by increased cutting frequency of the sward. Hughes *et al*., (1993) showed how defoliation could be successfully applied to dock management in grassland. In general, the consensus is that very frequent defoliations (~ every 2 weeks for 3 or more months) are required to keep dock populations from impacting on the grass DM production (Hopkins and Johnson, 2002; Stilmant *et al*., 2010; Van Evert *et al*., 2020). Defoliation in the establishment period (after reseeding) also reduces dock numbers and dock root biomass (Van Eekeren *et al*., 2006).

In addition to manipulating the competitive ability of desirable pasture species, animals grazing pasture can also affect weeds directly. The grazing may reduce the weed in a range of ways including: (1) killing the plant; (2) reducing flowering and seed output and hence subsequent recruitment opportunities or (3) reducing carbohydrate allocation to underground structures (roots and rhizomes) in plant species reliant on this reserve for their continued growth and perennation (e.g., creeping thistle in Bourdot *et al*., 1998 and Eerens *et al*., 2002) and docks in Zaller, 2004). While cutting frequency has been proven to reduce dock herbage DM production, almost no experiments have been conducted with livestock to manage dock populations (Zaller, 2004). One of the few actual grazing experiments was Hejcman *et al*. (2014) who recorded a reduction in flowering and eventually elimination of docks when dock infested pastures were stocked continuously for four years with goats, while Zaller (2006) also showed that certain breeds of sheep will selectively graze docks in pastures and eliminate them.

2.10.2. Crop Rotation

The concept of crop rotation as a weed management tool is to create a dynamic environment that will not favour the development of large populations of any one weed species (Naylor, 2002). In a grassland farm, alternating grazing and silage fields and having a targeted re-seeding program are examples of grassland crop rotations. Section 2.10.1 showed that increasing the cutting frequency greatly reduced the impact of docks on grass herbage DM production. Even though the experimental work on this aspect of dock control was conducted without actual animal grazing, survey work by Humphreys *et al*. (1999) confirmed that silage fields have greater dock densities than grazing fields.

Targeted re-seeding (where appropriate) allows the application of systemic herbicides (glyphosate) which will greatly reduce the viability of established dock root systems. This strategy exposes the dock population to a different 'environment' and 'shifts the point of attack' towards the dock seedling. In Ireland, the application of the herbicide glyphosate is a recommended and widely adapted practise when rejuvenating grassland (Creighton *et al*., 2011). Glyphosate facilitates the reseeding process, especially grass following grass, as it is a very effective herbicide for the control of grasses and deep-rooted perennial weeds including docks due to it being translocated throughout the whole plant including root, rhizome and stolon systems (Haggar, 1985).

2.10.3. Crop Establishment

It has been shown by Hongo (1989a); Jeangros and Nosberger (1990) that newly sown pastures contain abundant numbers of dock seedlings arising from the cultivation process stimulating seeds in the soil profile to germinate. Detailed dock germination and emergence studies (Hongo, 1989a; Jeangros and Nosberger, 1992 and Keary and

Hatcher, 2004) have shown that dock seeds have a better chance of surviving beyond the establishment phase if there is scarce competition by the surrounding vegetation. This is favoured by the complete removal of above and below-ground vegetation when reseeding. Also, it is favoured by open, poorly established grass swards if the reseeding procedure has not been successful. Dock seeds have the capability to germinate across a wide range of environmental conditions (Hongo, 1989a) but mainly die out from competition during the establishment phase especially at the cotyledon stage. In pot trials (Humphreys, 1995) showed that the greater ground cover achieved by white clover/perennial ryegrass swards significantly reduced dock seedling emergence compared to ryegrass swards alone. Ringselle (2019) found that adding a companion crop (spring barley) to the grass seed mixture was a reliable way to reduce dock numbers. Armstrong *et al*. (2001) showed similar effects of increasing perennial ryegrass density reducing ragwort seedling emergence. Based on this research, it seems plausible that establishing a grass/clover sward will result in less dock seeds germinating than establishing a pure stand of perennial ryegrass and it is also concluded that by establishing a vigorously growing, dense grass sward, germinating dock seedlings will have lower emergence and establishment rates. It also seems sensible that any intervention to increase the competitiveness of the sward around reseeding time will reduce dock seedling establishment.

2.10.4. Biological Control

The use of biological control agents for management of grassland weeds is well researched such as *Sclerotinia sclerotiorum* for controlling creeping thistle (Hurrell and Bourdot, 1996 and Bourdot *et al*., 2006); *Phoma macrostoma* also for controlling creeping thistle (Kluth *et al*., 2005 and Evans *et al*., 2012) and sunflower leaf extract for controlling *Rumex denatus* (Anjum and Bajwa, 2007). However, these techniques are not widely used in conventional grassland farming in Ireland (Creighton *et al*., 2011). A more comprehensive review of biological control agents for docks is in Cavers and Harper (1964) and Zaller (2004) and their application in grassland weed control is in Hatcher and Melander (2003). The most thoroughly studied organisms are the dock beetle *Gastrophysa viridula* and the rust fungus *Uromyces rumicis*.

2.10.4.1. Dock beetle

The dock beetle (*Gastrophysa viridula)* was seen to be the most promising of the pests and was reviewed by Martinkova and Honek (2004). The small leaf feeding beetle is unique to curled (*Rumex crispus* L.) and broad-leaved docks. It overwinters as an adult and emerges in April. Eggs are laid on the underside of leaves in batches of around 30. Adult beetles are most numerous in summer months and up to 3 generations are possible each year. In the field, a natural population of beetles can remove 45% of the leaf area of a dock (Zaller, 2004). Heavy grazing by the beetle can significantly reduce whole plant dry weight of both dock species, potentially resulting in a 65% reduction. However, the findings of Van Evert *et al*. (2020) show that even with intensive defoliation, dock roots recover and are not killed. Summarising beetle experiments, Zaller (2004) concluded that it was rare for dock plants to die out because of beetle grazing unless some other agent further weakened the plant or that the dock plant was stressed from an environmental condition. It is important to know the management practices that impact on beetle populations and effectiveness. The application of the herbicide Asulam to docks can reduce beetle numbers as it reduces their food source (Speight & Whittaker, 1987). Cutting and mowing of docks at critical stages can also have a major effect on beetle populations due to the limited dispersal of the adults (3 m to 7 m). An innovative Irish company, Green Submarine has commercialised the breeding of dock beetles to make them available for field scale dock management (Donovan, 2022).

2.10.4.2. Rust fungus

Rust has also been shown to give reductions in dock seed production, regeneration, and leaf and shoot growth but not sufficiently reduce its impact on grass DM production or eliminate docks (Hatcher, 1996; Hatcher and Ayers, 1998). Studies have shown that combinations of herbivorous beetles and fungi may produce more effective results. Grossrieder and Keary (2004) concluded that the augmentation of natural enemies was the best approach for dock control in organic agriculture in Switzerland, but it still required further study to determine whether it could be developed into a management tool for dock control. Hatcher (1996) found that combining beetle grazing and applying a rust fungus to the docks gave an additive effect reducing shoot and root dry mass by 80 % and 77% respectively. Taking this a step further, Keary and Hatcher (2004) investigated the effects of beetle grazing and rust infection on docks grown in competition with grass. They found that dock seeds when sown at the same time and 21 days after the grass seeds showed a reduction in total weight of 7.4% and 40.3% respectively compared to docks sown without grass competition. This would suggest that if grass can be encouraged to establish quickly, it is competitive against dock seedlings.

2.10.5. Crop Nutrition Strategy

One of the fundamental criteria for maintaining a dense competitive grass sward is having a balanced crop nutrition program. It is also beneficial to understand the relationship between weeds and key nutrients and exploit any interactions that may exist to improve crop growth, minimise weed growth and possibly enhance herbicide efficacy. Excessive nutrients leading to environmental problems are not only wasteful but may be exasperating a particular weed problem such as potassium and docks (Humphreys *et al*., 1999), nitrogen and docks (Niggli *et al*., 1993), and nitrogen and sheep sorrel (*Rumex acetosella*; Kennedy *et al*., 2011). Other researchers have looked at altering nutrient applications and/or application timings in the crop or weeds lifecycle to manage weeds such as: nitrogen and weed control in winter wheat (Blackshaw (2004); various weeds and potassium and sulphur (Grant *et al*., 2006); lime and rush control (Smolders *et al*., 2008); phosphorous in lettuce weed control (Odero and Wright, 2013); nitrogen and control of fat hen (*Chenopodium album;* Lindsey *et al*., 2013); nitrogen and control of stinging nettle (Mullerova et al., 2014).

Weeds also remove large quantities of expensive nutrients and by competing with the crop, reduce yields which may be impossible to recover even if the weeds are controlled (Lehoczky *et al*., 2005). When examining possible interactions between herbicides and nitrogen, Sonderskov *et al*. (2012) found that nitrogen rate affected herbicide efficacy for some but not all combinations of weed species and herbicide. However, the effects were marginal and only evident under very low nitrogen systems.

These preceding examples highlight the potential of integrating crop nutrition approaches in tackling pasture weeds (Hatcher and Melander 2003). Future research needs to consider what combinations give the most effective weed control, in particular interactions between grazing management and either classical or innovative biological control methods.

2.11. Integrated Weed Management

Integrated Weed Management (IWM) is a strategy that uses potential synergisms between biological, chemical and cultural control methods to reduce weed populations below an economic threshold (Naylor, 2002; Young, 2012).

2.11.1. Defining IWM

Numerous definitions have been applied to IWM and the broader area of integrated pest management (IPM). Harker and O' Donovan (2013) defined IWM as the use of more than one weed management tactic (biological, chemical, cultural, or physical) during or surrounding a crop life cycle in a given field and noted that "successful IWM techniques are most likely to be discovered after biological characteristics and ecological behaviours of weeds have been elucidated". A key component of developing a successful IWM strategy (and the future of weed science) is knowledge of the weeds themselves especially population biology and ecology of weeds (Zimdahl, 1994). Harker and O'Donovan (2013) visually described possible IWM systems including several different combinations of weed control methods. In modern agriculture with increased scale, reducing labour and an over-reliance on quick-fix solutions, not many of these systems combine all weed management methods (Figure 2.2). However, increasingly and probably due to increased levels of herbicide resistance, many current IWM systems do involve chemical and physical/cultural (Figures 2.2 B and 2.2 C). Figure 2.2 D was classed by Harker and O' Donovan (2013) as not being IWM due to it being solely reliant on herbicides.

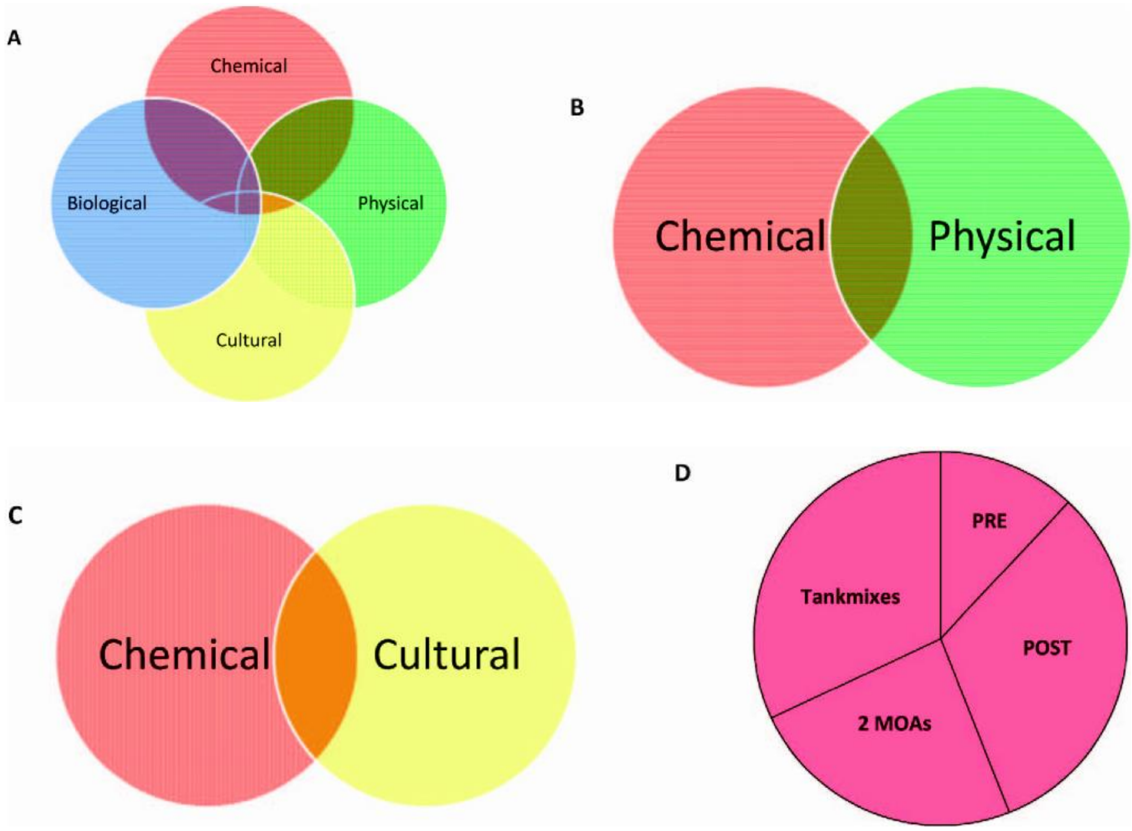


Figure 2.2 Some forms of true integrated weed management (IWM) (A–C) in contrast to integrated herbicide management (D). (Harker and O'Donovan, 2013)

2.11.2. Rationale for using IWM and associated problems

Herbicides are the principal method of weed control in modern agriculture but are a blunt instrument to overcome the complex problem presented by weeds in an agricultural system. To illustrate this point, consider one of the rapidly increasing problems in modern agriculture – the evolution of herbicide-resistant (HR) weeds (Beckie, 2006). Globally, there are 383 HR weed biotypes among 208 HR weed species (Heap, 2014) including many cases of weeds being resistant to glyphosate (most widely used herbicide in the world) and widespread multiple herbicide resistance within single biotypes. A key approach of IWM is to try to minimise the occurrence of weed problems in crops by increasing crop competition and to manage weed populations using cultural, biological as well as chemical solutions. However, IWM is not easily adapted due to a multitude of factors as described by Llewellyn *et al*. (2004) and Pannell (2002). In the latter authors study of IWM and its adaptation to combat herbicide resistant weeds in the Australian wheat belt, he found that farmers were quite knowledgeable regarding resistance, but still believed that a new chemical solution was imminent. Citing management decisions such as crop rotations, soil and cultivation practices, crop nutrition strategy and other aspects of crop protection etc. are all integral to developing a successful integrated weed management strategy. It is also critical to re-assess the dynamic changes in weed flora so that the IWM system can evolve.

One of the problems of IWM is the very nature of using multiple tools to manage weeds leads to complicated experimental situations. Also, there are physical and economic limitations in designing true IWM experiments. Many researchers often quote the limitations of designing an experiment when trying to include crop rotation components, different animal grazing pressures (Pywell *et al*., 2010), combining cutting with herbicides (Lowday and Marrs, 1992) or allowing an experiment to continue for a sufficient period to allow the true effects to become apparent e.g. Huwer *et al.* (2005). Zaller (2004) identified that longer term manipulative field experiments were needed to assess the combined effects of several non-chemical control measures on Rumex species. However, given the obvious threat to the long-term viability of herbicides, researchers, agronomists and farmers will have to embrace IWM to improve the efficacy, longevity and public acceptance of herbicide use in food production.

2.11.3. IWM in grassland

The rise in herbicide resistance and the reduction of new herbicides becoming available has driven research and 'forced' the adaptation of IWM in arable crops (Panell, 2002). It is generally accepted that the frequency of herbicide resistant plants increases slowly in the presence of continued herbicide application. Thus, herbicide selection pressure is considered as one of the primary causes for the evolution of herbicide-resistant biotypes (Mithila *et al*., 2011). The same authors considered the situation of why there are so few reported incidences of herbicide resistance in turf grass and lawn care. They postulated that it may be due to a number of factors including competition from grass, herbicide application methodology or, worryingly, a lack of monitoring for herbicide resistance in turf grass and amongst householders in a lawn situation. This could be considered a reasonable proxy for herbicide resistance in intensively managed grasslands. There are very few published accounts of herbicide resistance in grassland. One exception is common chickweed (*Stellaria media* L.) was found to have developed resistance to the phenoxy herbicide Mecoprop in the UK (Putwain and Mortimer, 1989; Lutman and Snow, 1987). In New Zealand, grassland has been very intensely managed, and pesticides have been commonly applied over many years and herbicide resistance is evident in grassland weeds (Bourdot *et al*., 2007; Lusk *et al*., 2011). This has driven non-chemical or more targeted approaches to weed control (Moyo, 2008). Another driver of IWM in grassland is legislative e.g., the Sustainable Use Directive. This was expanded in section 2.9.5.2

2.11.4. Applications of IWM in grassland

There have been notable successes of applying IWM in grassland, most likely due to the highly competitive nature of grassland and lack of large-scale soil disturbance events (such as annual tillage operations in arable fields). Lowaday and Marrs (1992) and Petrov and Marrs (2001) both showed that integrating chemical with a cultural control technique (either cutting and fertiliser strategy) was beneficial for the control of bracken. Mitchell and Abernethy (1993) showed that creeping thistle can be successfully controlled by a combination of topping, herbicide application and grazing management. Edwards *et al*. (2002) demonstrated how creeping thistle populations were reduced by a combination of competition from the grassland and altering soil fertility. They recorded superior control of thistle than other authors using either herbicide alone (Meeklah and Mitchell, 1984) or mechanical alone methods (Donald, 1990). Huwer *et al*. (2002) and Huwer *et al*. (2005) demonstrated that broad-leaved weeds can be reduced when high level pasture background management and chemical control are combined rather than used in isolation. They also showed that depending on the site, various components of the IWM strategy need to be modified in order to achieve a desirable result and that it may take a number of years to realise results. Suter *et al*. (2007) showed how grazing and cutting practices can reduce the incidence of ragwort. Hatcher and Melander (2003) reviewed biological control of many weeds and outlined that using interactions between physical, cultural and biological methods gave better results of weed control than either aspect alone. They did not consider chemical methods so in the strict sense of IWM, omitted a component of a truly IWM system. Zaller (2004) and Bond *et al*. (2007) comprehensively reviewed the non-chemical control of docks which are components of IWM strategies.

2.11.5. IWM and the control of broad-leaved docks in Irish grassland:

There are many examples of how plant competition reduces weed establishment and growth. Therefore, the essential principle of cultural control of Rumex in grassland is that the sward is competitive (Zaller, 2004). This can be achieved by optimising seeding rates, fertiliser strategies, stocking rates and conservation regimes to achieve a competitive pasture sward. There are many examples of how the impact of plant competition reduces weed establishment and growth. Keary and Hatcher (2004) and Humphreys (1995) showed that docks are susceptible to competition stresses from increased seeding rate of PRG and clover during establishment. In pot trials (Humphreys, 1995) showed that the greater ground cover achieved by white clover/perennial ryegrass swards significantly reduced dock seedling emergence compared to ryegrass swards alone. In existing swards, weeds are less likely to establish when the gap size is small due to shading and where the incidence of bare ground is low due to deployment of grazing regimes in the spring and autumn (Panetta and Wardle 1992 and Edwards *et al*., 2005). Based on this, you can expect that weed population sizes will be minimised in pastures that support a high proportion of perennial grasses, and which are grazed in a manner that limits the creation of small- to medium-sized bare patches in the pasture at key stages in a weed species lifecycle.

There have been very few experiments conducted to manage docks using herbicides in combination with other cultural control methods. Speight and Whittaker (1987) examined possible synergies between the dock herbicide Asulam and the chrysomelid beetle *Gastrophysa viridula*, known to feed on dock plants. They found that Asulam treated plants were not a good environment for *G. viridula* probably due to the lack of high-quality foliage rather than a direct effect on the beetles themselves and that no synergistic relationship between Asulam and beetle grazing was evident. The difficulties in prescribing practical agronomic advice are highlighted by their recommendation to only spray Asulam during pupation/adult emergence. This occurs after mid-summer when most of the yield penalty from docks would have occurred.

2.12. Conclusions from Literature Review

Grassland is a critical driver of Irish agriculture, and its productivity can be significantly eroded by docks.

Modern grassland management practices, essential for efficiency and profitability, are conducive to dock recruitment (reseeding) and biomass production (silage making and fertiliser applications). In general, docks are favoured by fertile soils and infrequent cutting.

There is an impressive body of literature on the biology and control methods (herbicide and non-herbicide) of docks.

The general aim of these control methods is to prevent the build-up of dock seeds and reduce the re-growth capacity of docks by removing or weakening the above and below ground biomass.

Recent innovations in non-herbicide control of docks such as targeting the roots or targeting the foliar growth have not been widely adopted by intensive grassland farmers.

Intensive grassland farmers require a rapid, robust, and economic method of dock control; thus, herbicides are still the most popular dock control option, despite their limitations (i.e., require repeat applications).

However, further legislative restrictions on herbicides will reduce their availability and latitude of farmers to apply them as required.

It is imperative for intensive grassland farmers that innovative and novel dock control methods are researched and disseminated in advance of potential legislative changes.

Chapter 3 Effectiveness of dock (*Rumex obtusifolius* L.) control in new leys and established grassland following the application of herbicides

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Abstract

Docks are a widespread problem in intensively managed grassland, requiring repeated pesticide applications for control purposes. New European Union pesticide regulations aim to restrict pesticide use. This necessitates improved efficiency of pesticide use including the most effective time to apply them during the target weed's lifecycle. The experimental site (52°21N, 7°18W) was reseeded with perennial ryegrass in October 2009. A plot (5m x 10m) experiment was laid down in a randomised complete block design with nine treatments and eight replicates. Four herbicides licensed for use in new leys (NLH) were each applied in April 2010. Four herbicides licensed for use in established grassland (EGH) were each applied two years later in April 2012. The ninth treatment was an untreated control. Dock numbers were measured over five years (2010–2014) and herbage production over three years (2012–2014). Across all treatments dock numbers were relatively low until the fourth year during which there was more than a three-fold increase due to clonal propagation. NLH gave more ($P<0.001$) effective and enduring control than EGH. EGH varied in their effectiveness with ($P<0.001$) recovery of individually marked docks that were 'apparently dead' following EGH application. In 2014 dock herbage dry matter (DM) production (t ha^{-1}) was 3.41 in the control compared with 0.55 for NLH and 1.38 for EGH. Across all treatments in 2014 grass DM production declined with increasing dock herbage DM production (t ha^{-1}): grass = 11.17 – 1.047 × dock (R^2=0.73; $P<0.001$). More eco-efficient control of docks was achieved by herbicide application to new leys.

Keywords: Docks, Rumex obtusifolius, Grassland, Herbicide, New ley

3.1. Introduction

Broad-leaved dock (*Rumex obtusifolius* L.) hereafter described as 'dock' or 'docks' is a very common weed of intensively managed temperate grassland (Courtney, 1985; Hopkins, 1986; Creighton *et al.*, 2011). Intensive grassland management practices, common on dairy farms, such as high input of synthetic fertilisers, land spreading of organic manures and grass-silage production have all been associated with the increasing abundance of docks (Hopkins and Peel, 1985; Humphreys *et al.*, 1997). For example, Humphreys *et al*. (1999) recorded dock populations ranging between 0 and

3.15 m^{-2} in swards used for grazing and silage production. At low population densities docks were considered to be of little consequence for grass production but at higher ground cover, which is a combination of dock population density and the size of individual docks, they were considered to lower both the productivity of the sward (Oswald and Haggar, 1983; Courtney, 1985; Hopkins and Johnson, 2002) and intake by grazing animals (Courtney and Johnston, 1978, Derrick *et al.*, 1993). During grassland establishment old rootstocks have been shown to be capable of regeneration (Zaller, 2004). However, on intensively managed farms a non-selective herbicide (glyphosate) is typically applied prior to cultivation that kills existing rootstocks (Creighton *et al.*, 2011). Hence, the recruitment of seedling docks is often the primary source of docks in newly sown grassland. There is an ample supply of viable dock seeds in the soil and the seedlings can get established before the newly sown grassland is fully competitive. Seedling docks tend to be more vulnerable to control measures during this stage of their lifecycle (Hongo, 1989a; Humphreys *et al*., 1997; Keary and Hatcher, 2004; Bond *et al*., 2007).

Once established, docks produce a deep taproot with a large storage capacity for assimilates, which, along with other adaptations, make the mature dock plant very resilient and competitive in grassland (Niggli *et al*., 1993; Hopkins and Johnson, 2002; Stilmant *et al*., 2010; Strnad *et al*., 2012). The control of docks is almost exclusively by selective herbicides, which can often be of moderate effectiveness and generally short-term with further applications required (Savory and Soper 1973, Haggar, 1980; Oswald and Haggar, 1983; Mitchel, 2001; Hopkins and Johnson 2003). Recent innovations in non-herbicide control of docks such as targeting the roots (Van Evert *et al.,* 2011., Latsch *et al.,* 2017) or targeting the foliar growth (Stilmant *et al*., 2010, Hejcman *et al*., 2014) or experimental approaches such as using targeted microwaves (Latsch, and Sauter, 2010) have not been widely adopted by intensive grassland farmers (Creighton *et al*., 2011). Such farmers require a rapid, robust, and economic method of dock control; thus, herbicides are still the most popular dock control option, despite their limitations. The Sustainable Use of Pesticides Directive (SUD), Directive 2009/128/EC (Anon, 2009) places a legal framework on the general principles of reducing pesticides in agricultural production in favour of techniques such as the use of cultural techniques and timeliness of pesticide application to optimise efficacy. A survey of grassland establishment practices on dairy farms in Ireland showed that 89% of farmers apply glyphosate to kill off the old sward but only 53% routinely applied a post-emergence herbicide (Creighton *et al.*, 2011). In future, the EU plans to cut pesticide use by 50 % (Anon, 2020) and given that 96% of the pesticides applied to Irish grassland are herbicides (Anon, 2019), it is imperative that herbicides are applied to grassland as effectively as possible.

Most of the published work on herbicide control of docks was carried out on mature docks where the control was monitored over a relatively short timescale; 12 to 24 months following treatment (Savory and Soper, 1973; Oswald and Haggar, 1976; Mitchell, 2001; Hopkins and Johnson, 2003 and Creighton *et al*., 2010). There has been very little published research on using herbicides to control seedling docks and we are not aware of any study comparing the efficacy of herbicide control of seedling docks in newly established grassland and mature docks in established grassland.

Our hypothesis was that NLH would give more effective, eco-efficient (lower application rate of herbicide) and long-term control than EGH. NLH were aimed at controlling the initial flush of seedling docks during grassland establishment while the grass sward was less competitive than an established sward. Hence, the objective was to quantify the long-term effectiveness of dock control when herbicides were applied as NLH or EGH in terms of application rates, dock numbers and impact on grass production.

3.2. Materials and Methods

3.2.1. Experimental site

This experiment was conducted between September 2009 and September 2014. The site (52°21N, 7°18W and 20m ASL) had previously been cropped under intensive arable cropping; wheat, barley, oats and maize grown in a six-course rotation. In October 2009, the field was ploughed to 20 cm, cultivated with a power-harrow and fertilized with 370 kg ha^{-1} of a compound fertiliser containing 10% N, 10% P and 20% K. The field was then sown with perennial ryegrass *(Lolium perenne* L.; cv. Tyrella, a late flowering diploid and Bealey, a late flowering tetraploid) at a seeding rate of 35 kg ha^{-1}. In November 2009, dock seedling numbers were assessed using a 0.25m^2 quadrant, laid down randomly every 10 m along 100 m length transects across the experimental site. *R. obtusifolius* L. was identified according to Farragher (1996). It was the predominant dock species in the sward. There was a very low abundance of *R. crispus* and hybrids between these two species.

The monthly mean rainfall and temperature during the experiment are presented in Figure 3.1. The soil of the experimental area was sampled in spring 2010 and results showed that the soil pH was 6.3 and soil P and K concentrations were adequate according to soil test results (6.1 and 124 mg L^{-1} respectively following extraction using Morgan's solution (Na acetate + acetic acid, pH 4.8). To put these concentrations in context, no agronomic response is expected at soil Morgan's P >8.0 mg L−1 and soil Morgan's potassium >150 mg L^{-1} (Coulter *et al*., 2008). Each year the experimental area received fertilization rates of 250 kg N ha^{-1}, 40 kg P ha^{-1} and 200 kg K ha^{-1}. Ground limestone was applied at a rate of 5 t ha^{-1} in spring 2013 in line with soil test results.

3.2.2. Experimental design and treatments

Plots (10 m x 5 m) were laid down in November 2009. The experiment was a randomized complete block design with eight replicated blocks. There were nine plots per block. Herbicide treatments were randomly assigned to plots within each block. Herbicide treatments were selected based on approved product registration and all products were applied according to manufacturer's recommendations. There were two categories of herbicide treatments: (i) herbicides applied at the new ley stage (NLH), i.e. a single application of herbicide on 29 April 2010 and (ii) herbicides applied to established grassland (EGH); i.e. a single application of herbicide on 23 April 2012. Therefore, the plots receiving EGH were managed in an identical manner to the control treatment from establishment until EGH application. There were four herbicides per category (Table 3.1). The appendages to Doxstar treatments in Table 3.1 i.e. Doxstar-NLH and Doxstar-EGH was to differentiate between Doxstar applied as an NLH and as an EGH in the present study. Each of the herbicide treatments were carefully applied in calm weather using a hand-held Azo propane plot sprayer calibrated to deliver 220 L ha^{-1} using 025 flat fan nozzles at a constant pressure of 2 bar. To reduce spray drift, a 50 cm wide uncropped area delineated each plot. There was also an untreated control that received no herbicide application.

Table 3.1. Herbicide treatments applied to new ley grassland (NLH) were applied on 29th April 2010 and herbicides applied to established grassland (EGH) were applied on 23rd April 2012.

Herbicide name	Rate of application, active ingredients and manufacturer
New ley herbicides (NLH)	
Alistell	3.5 L ha^{-1} Alistell (Linuron 30g L^{-1} + 2, 4-DB 220g L^{-1} + MCPA 30g L^{-1}; United Phosphorus Ltd.)
Legumex DB + Triad	5.0 L ha^{-1} Legumex DB (MCPA 40g L^{-1} + 2,4-DB 240g L^{-1}; Hygeia Chemicals Ltd.) + 10 g ha^{-1} Triad (Tribenuron-methyl 50% w/w; Headland Agrochemicals Ltd.)
Duplosan KV	2.5 L ha^{-1} Duplosan KV (Mecoprop-P 600g L^{-1}; Nufarm UK Limited)
Doxstar-NLH*	1.5 L ha^{-1} Doxstar (Fluroxypyr 100g L^{-1} + Triclopyr 100g L^{-1}; Dow AgroSciences)
Established grassland herbicides (EGH)	
Eagle	60 g ha^{-1} Eagle (Amidosulfuron 75 % w/w; Bayer Crop Science Ltd.)
Prospect SX	22.5 g ha^{-1} Prospect SX (Thifensulfuron-methyl 500 g kg^{-1}; Du Pont (U.K.) Ltd.)
Doxstar-EGH*	3.0 L ha^{-1} Doxstar (Fluroxypyr 100g L^{-1} + Triclopyr 100g L^{-1}; Dow AgroSciences)
Forefront	2.0 L ha^{-1} Forefront (Aminopyralid 30 g L^{-1} + Fluroxypyr 100 g L^{-1}; Dow AgroSciences)

*Differentiates between Doxstar applied as an NLH and as an EGH.

Description of the docks and grass on the dates when herbicides were applied

Prior to the application of NLH in April 2010, most seedling docks had three or four leaves, with the largest leaves being 50 mm in width and 100 mm in length and were actively growing. The dock tap roots were less than 10 mm in diameter at the root collar and less than 150 mm in length and all the examined dock roots were deemed to be emanating from seeds. The compressed sward height was 8.5 cm tall measured using a Filips rising plate meter (Grasstec) and was actively growing at the time of application. No rainfall was recorded for 24 hours before or after application and the average daily temperature for the week before spraying was 12.2°C and 9.5°C the week after spraying. Growing conditions for April and May 2010 were typical for that time of the year with adequate rainfall (106 mm rain) but slightly below normal temperatures (9.0 and 11.5°C respectively; see Fig 3.1). These conditions were suitable for applying herbicides according to the manufacturers' recommendations.

Prior to the application of the EGH in April 2012 the majority of the docks had at least 4 leaves, with the largest leaves being 150 mm in width and 250 mm in length, with well-developed tap roots (>25 mm in diameter at the root collar and >250 mm in length) with some plants exhibiting clonal fragmentation as described by Pino *et al*. (1995). The docks were actively producing new growth with no foliar disease and no visible herbivory. The compressed sward height was 9.0 cm tall measured using a rising plate meter and was actively growing at the time of application. No rainfall was recorded for 24 hours before or after application and the average daily temperature for the week before spraying was 8.8°C and 8.2°C the week after spraying. The months of April and May 2012 were slightly cool (7.7 and 11.3°C respectively) and had adequate rainfall (112 mm), see Fig 3.1. These conditions were suitable for applying herbicides according to the manufacturer's recommendations.

3.2.3. Experimental measurements

Dock population densities

Assessments of dock ramet density were made on two occasions in each of the five years of this study, in March (spring) and in September (autumn). For the assessments in 2010 and 2011, when the individual dock plants were quite small, a 0.25 m^2 quadrant was laid down at random 10 times in each plot and the number of visible dock ramets counted in the quadrant and expressed as the average number of docks m^{-2}. For subsequent assessments (2012 to 2014), the total number of visible dock ramets was counted in each plot and expressed as docks m^{-2}. A dock ramet was defined as having at least 4 leaves arising from one shoot according to Humphreys *et al*. (1999). Detailed assessments were made of selected dock ramets to validate the whole plot assessments.

The impact of EGH on individually marked docks

Prior to applying the EGH in 2012, a steel nail (100 mm long) was placed immediately adjacent to each of ten dock ramet crowns selected randomly in each of the plots receiving the EGH and the untreated control. Each nail was pushed vertically into the soil with the upper end at the soil surface in order minimise disturbance by grazing cows or passing machinery. The location of each nail within each plot was recorded on a 0.1 m by 0.1 m plastic grid laid over each plot. At 6, 12 and 18 months after the application of EGH the steel nails used to mark each dock were located using the grid and a metal detector (Model AF 350, Whites Electronics, Inverness, Scotland). Each marked dock ramet was assessed as being either 'apparently dead' (no visible foliar growth from the marked dock ramet crown) or 'alive' (exhibiting foliar growth from the marked dock ramet crown). In September 2013, all the nails were excavated and associated surviving dock roots were carefully harvested by hand. Only dock roots physically attached to the dock ramet crown immediately adjacent to the steel nail was assessed and weighed. The root of each dock was carefully separated from the shoot component in the laboratory by cutting each crown at the lowest leaf scar. The roots were washed and both roots and shoots were dried to a constant weight at 105 ^{0}C in a forced draft oven to determine DM weight.

Herbage Yields

The experimental area was grazed by dairy cows in March each year and subsequently closed for silage. First-cut silage was harvested in late May. A second cut of grass for silage was taken in July. Subsequently, the experimental area was grazed rotationally by dairy cows until the end of October in line with typical grassland management. Prior to harvesting each silage cut the herbage on each plot was harvested using a Haldrup plot harvester (J. Haldrup, Lùgstùr, Denmark) on 21 May and 30 July 2012 and 24 May and 10 July 2013 and 22 May and 23 July 2014. Herbage was harvested from a 10 m long by 1.5 m wide strip along the centre of each plot and weighted to determine fresh weight per plot. A subsample of 300 g of fresh herbage was collected from each plot and weighed before and after drying at 105°C for 16 hours in a forced draft oven to determine the dry-matter (DM) content. The herbage from a second set of subsamples (approximately 1000g) from each plot were separated by hand into dock and other herbage before drying at 105°C for 16 hours in a forced draft oven to determine the relative proportions of docks and other herbage (predominantly perennial ryegrass and other unsown grass species) on a DM basis.

3.2.4. Statistical analysis

Dock ramet numbers per plot at each assessment date for each of five years were transformed using a natural log (y=log(x+1)) and were analysed using a two-factor (herbicide treatment x sampling date) ANOVA examining the main effects of each factor and interactions between factors, with eight replicates. Dock ramet numbers per plot at the start of the experiment (spring 2010) were used as a covariate in this analysis. All statements on significance are based on the transformed values. Untransformed data are presented in Table 3.2 to aid clarity.

Grass herbage DM yields were each summed for each year (2012, 2013 and 2014) and subjected to ANOVA within each year and to a two-factor (herbicide treatment x year) ANOVA. Likewise for dock herbage DM and total (grass and dock) herbage yields were similarly subjected to ANOVA.

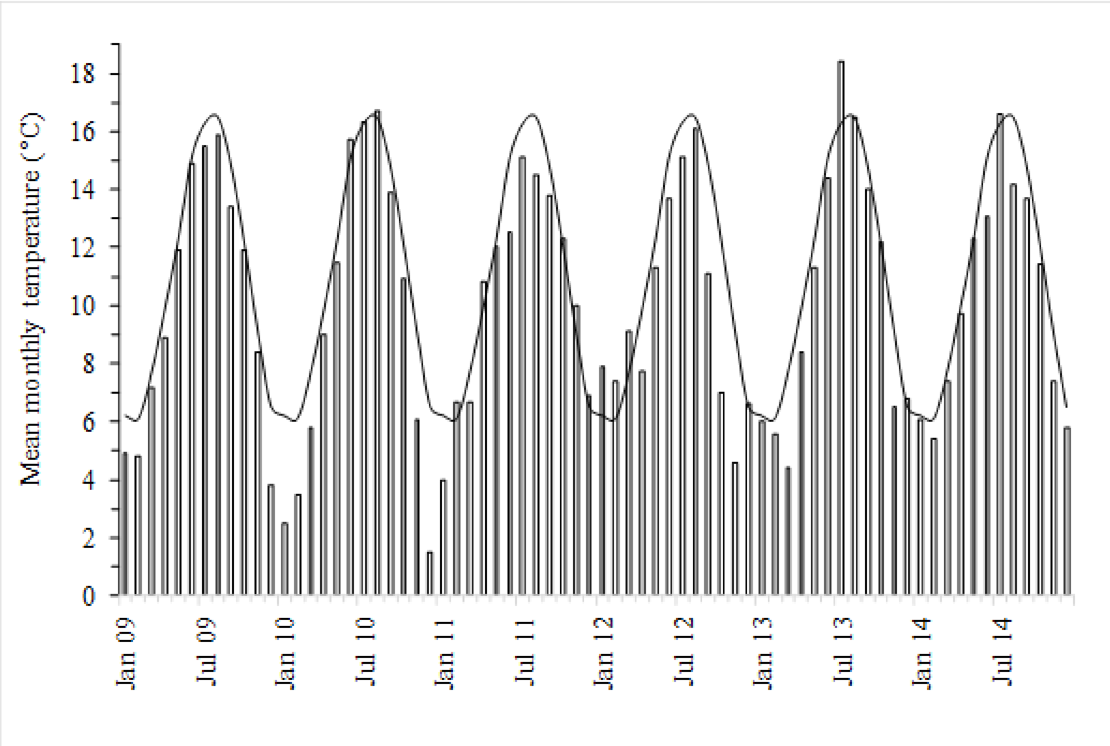
Marked dock numbers were subjected to a two-factor (herbicide treatment x sampling date) ANOVA with sampling date included as repeated measures examining the main effects of each factor and interactions between factors, with eight replicates. Marked dock herbage and root weights were subjected to a single-factor (herbicide treatment) ANOVA with eight replicates. The relationship between dock herbage yields and grass herbage yields were examined using linear regression. The software package MSTAT was used for statistical analysis.

3.3. Results

3.3.1. Meteorological data

Meteorological data was obtained from a Met Eireann (www.met.ie) weather station approx. 800 m from the experimental site. The mean annual air temperature was lower in each of the five years of this study than the previous ten-year average (11°C). The winters of 2009/2010 and 2010/2011 were exceptionally cold (Figure 3.1). The annual rainfall amounts each year were similar to the ten-year average (1073 mm). The rainfall during November 2009 was twice normal and there was exceptionally high rainfall during the months of June and August 2012.

(a)



(b)

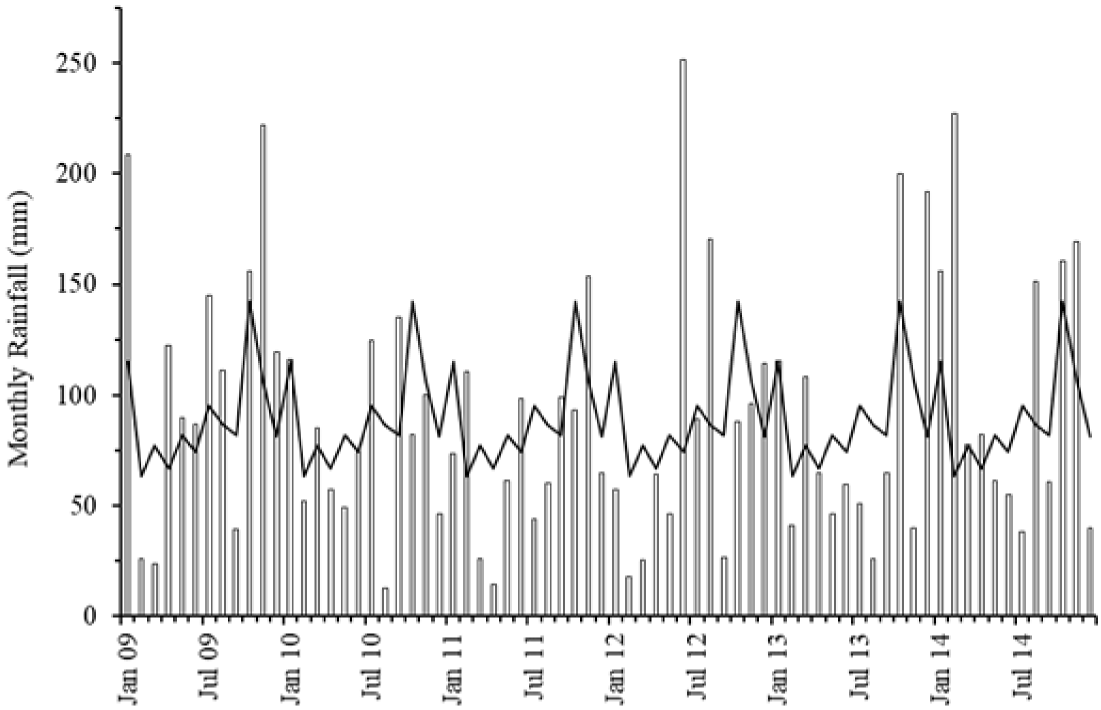


Figure 3.1. Monthly air temperature (a) and monthly rainfall (b) at the experimental site between 2009 and 2014. The columns show the levels during the experiment and the lines show the averages of the previous ten years

3.3.2. Dock Numbers

On average across the experimental site there were 8.1 dock seedlings m^{-2} (SD = 4.1) in November 2009. By the following spring 2010, the average number of dock seedlings in the untreated control and the yet to be treated EGH treatments was 6.6 plants m^{-2} (SD = 2.76) and declined further to 4.8 plants m^{-2} in autumn 2010 (Table 3.2). There was no change in dock numbers in the untreated control between autumn 2010 and spring 2013. However, between spring and autumn 2013 dock numbers increased (P<0.001) from 3.78 to 7.84 m^{-2} with a further (P<0.001) increase between autumn 2013 and spring 2014 and no further increase between spring and autumn 2014. There was a somewhat similar increase in dock numbers in each of the herbicide treatments within the same timeframe in this study. Across all treatments the number of docks present in autumn 2014 was proportional to the number present in spring 2013: Dock numbers in autumn 2014 = 1.78 + 2.87 × dock numbers in spring 2013 (R^2 = 0.81; P<0.001; Equation 1).

Each of the NLH had lower (P<0.001) dock numbers compared to the untreated control at each of the nine assessment dates during this study (Table 3.2). Apart from spring 2011, Alistell treated plots had more (P<0.001) docks than each of the other NLH treatments over the duration of the study. Between spring 2011 and the end of the study Doxstar-NLH ha lower (P<0.001) numbers than all of the other treatments.

In the assessments prior to application of the EGH i.e., between autumn 2010 and spring 2012, there was little or no differences in the number of docks per plot between the untreated control and the plots assigned to each of the EGH (Table 3.2). Following the application of EGH, there were no differences in docks m^{-2} between Eagle and the untreated control at any of the subsequent assessment dates. Prospect SX, Doxstar-EGH and Forefront had (P<0.001) lower docks m^{-2} compared to the untreated control for the remainder of the study. Of the latter three EGH Forefront was the most effective and Prospect SX was the least effective in terms of consequently lower dock numbers during 2013 and 2014 (Table 3.2).

In general, the NLH treatments resulted in substantially lower dock numbers during the study than the EGH (Table 3.2). On the last assessment date (autumn 2014) the most effective EGH (Forefront) had similar dock numbers to the least effective NLH (Alistell).

Table 3.2. The effect of herbicide treatment on dock abundance over five years

Sampling date:	Autumn 2010	Spring 2011	Autumn 2011	Spring 2012	Autumn 2012	Spring 2013	Autumn 2013	Spring 2014	Autumn 2014
	Number of docks m^{-2}								
Untreated	4.53	3.92	3.39	3.59	3.81	3.78	7.84	11.24	11.83
New ley herbicides (NLH)[1]									
	Post-application								
Alistell	1.94	1.59	1.49	1.52	1.69	1.59	3.35	5.25	5.39
Legumex DB + Triad	1.53	1.30	1.30	1.28	1.49	1.33	2.20	3.08	3.58
Duplosan KV	1.39	1.99	1.36	1.34	1.55	1.40	2.50	3.59	3.91
Doxstar-NLH	0.90	0.37	0.43	0.43	0.43	0.46	0.62	0.85	1.03
Established grassland herbicides (EGH)[2]									
	Pre-application				Post-application				
Eagle	5.08	3.57	3.44	3.45	3.13	3.03	6.57	9.73	11.78
Prospect SX	4.47	3.98	3.31	3.38	2.36	2.27	5.31	8.86	9.82
Doxstar-EGH	4.60	3.50	3.20	2.91	2.00	1.61	3.51	6.36	7.96
Forefront	5.38	5.18	3.79	3.84	1.15	0.69	2.86	5.46	5.84

	Herbicide	Sampling date	Herbicide x sampling date
P value	<0.001	<0.001	<0.001
SEM	0.201	0.438	0.604

[1]New ley herbicides applied on 29th April 2010

[2]Established grassland herbicides applied on 23rd April 2012

3.3.3. The impact of EGH on individually marked docks

The number of individually marked docks in the untreated control declined (P<0.001) during the study (Table 3.3). The application of EGH lowered (P<0.001) the number of marked docks compared to the untreated control and generally accorded with the impact that EGH had on dock numbers per plot described above with Eagle being the least effective and Forefront being the most effective at lowering dock numbers. In the EGH treatments lowest numbers of marked docks were recorded in autumn 2012 with a subsequent recovery of numbers particularly in the less effective EGH in the spring 2013 with no (P>0.05) change in the number of marked docks within each of the EGH treatments during 2013.

The DM weights of roots and shoots of individually marked docks per plot and per ramet in autumn 2013 followed the same trend as numbers of marked docks (Table 3.4). Application of EGH lowered both the DM yield of roots and shoots of marked docks per plot and per individual plant compared the untreated control. The impact of each EGH on dock numbers was reflected in the DM yield of both roots and shoots of individual docks in each treatment; the EGH that were more effective at lowering dock numbers also resulted in lower DM yields per individual plant (Table 3.4). There was no difference in the ratio (0.72; SEM = 0.024) of root: total root and shoot DM of marked docks between EGH treatments and the untreated control in the autumn 2013.

Table 3.3. The number of marked docks following the application of herbicides to mature docks in established grassland (EGH)

	Spring 2012*	Autumn 2012	Spring 2013	Autumn 2013
		Marked docks		
Untreated	10	9.9	9.5	9.0
Eagle	10	7.4	8.5	7.8
Prospect SX	10	4.9	8.3	7.8
Doxstar-EGH	10	2.4	4.6	4.5
Forefront	10	1.5	2.9	3.4
			P value	sem
Herbicide x sampling date			<0.001	0.44

*Number of marked docks prior to herbicide application

Table 3.4. Marked dock roots and total roots and shoots dry matter (DM) yield in autumn 2013 following the application of herbicides to mature docks in established grassland (EGH)

	Root	Total	Root	Total
	(g DM $plot^{-1}$)		(g DM $ramet^{-1}$)	
Untreated	283	418	30.9	45.2
Eagle	202	293	28.5	41.4
Prospect	167	236	20.4	28.9
Doxstar-EGH	77	105	18.0	24.3
Forefront	57	81	14.0	19.4
P value	<0.001	<0.001	<0.01	<0.01
SEM	31.4	49.5	3.54	5.24

3.3.4. Herbage DM Production

Total herbage (grass and dock) DM production (combined yields of first and second cuts) in the untreated control was 7.88 t ha^{-1} in 2012, 10.37 t ha^{-1} in 2013 and 11.03 t ha^{-1} in 2014. There was no difference in total herbage production between the NLH treatments and the untreated control (7.88 t ha^{-1}; SEM = 0.210) in 2012. All of the EGH had lower (P<0.001) total herbage production than the untreated control in 2012. In contrast there were no differences in total herbage DM production between treatments in 2013 (SEM = 0.236) and in 2014 (SEM = 0.308).

The main reason for lower total herbage DM production in the EGH treatments in 2012 was lower (P<0.001) yields of grass herbage DM (Table 3.5), particularly where Prospect SX was applied. There was no difference in grass herbage DM production between treatments in 2013. In 2014, the untreated control had lower (P<0.01) grass herbage DM production than each of the other treatments. Doxstar-NLH had the numerically the highest grass yields in 2014 although not different from Legumex DB+Triad and Duplosan KV, but higher (P<0.01) than Alistell and each of the EGH (Table 3.5). There was no difference in grass herbage DM production between the EGH in 2014.

The yield of dock herbage DM increased (P<0.001) across all treatments between 2012 and 2014, particularly in the untreated control (Table 3.5). There were no relationships between dock and grass herbage DM production in 2012 or in 2013. In 2014, grass herbage DM production declined with increasing dock herbage DM production (t ha^{-1}): grass = 11.17 – 1.047 × dock (R^2=0.73; P<0.001; Equation 2).

Table 3.5. The effect of herbicide treatment on dock and grass herbage yields (t DM ha^{-1}) from a two-cut silage system over three seasons (2012, 2013 and 2014)

	Dock herbage DM			Grass herbage DM		
Year	2012	2013	2014	2012	2013	2014
			(t DM ha^{-1})			
Untreated	0.35	1.44	3.41	7.53	8.93	7.62
New ley herbicides (NLH)						
Alistell	0.09	0.62	0.78	7.77	9.49	9.72
Legumex DB + Triad	0.03	0.39	0.75	8.02	9.97	10.73
Duplosan KV	0.04	0.30	0.52	7.91	9.68	10.34
Doxstar-NLH	0.03	0.03	0.17	7.51	9.99	11.40
Established grassland herbicides (EGH)						
Eagle	0.06	1.06	1.57	7.03	9.31	9.27
Prospect SX	0.07	0.67	1.33	6.76	9.42	10.15
Doxstar-EGH	0.05	0.50	1.42	7.26	9.61	9.91
Forefront	0.02	0.59	1.19	7.10	9.54	9.78
P value	<0.001	<0.01	<0.001	<0.001	NS	<0.01
SEM	0.035	0.216	0.470	0.209	0.282	0.594
		P value	SEM		P value	SEM
Herbicide		<0.001	0.173		<0.001	0.230
Year		<0.001	0.088		<0.001	0.172
Herbicide x year		<0.01	0.299		<0.05	0.398

3.4. Discussion

3.4.1. Dock numbers

Following reseeding there was a decline in the number of dock seedlings m^{-2} between November 2009 (8.1 m^{-2}) and March 2010 (6.0 m^{-2}), which was probably primarily due to competition from the grass sward combined with little or no further recruitment of new seedlings after closure of the sward canopy. Hongo (1989a) and Krist'alova *et al*. (2011) also reported substantial dock seedling mortality (40 and 78%, respectively) in the first winter. The winter of 2009/10 was unusually cold in the present study (>3.0°C below average in January 2010; Figure 3.1). Dock numbers in the untreated control and untreated EGH treatments continued to decline until the autumn 2010 similar to that in other studies (Keary and Hatcher, 2004; Humphreys *et al*., 1997; Courtney, 1985; Cavers and Harper 1964) with no further decline in the untreated control in the present study between spring 2011 and spring 2013 (Table 3.2).

An unexpected result was the big increase in the number of docks in each treatment between the spring 2013 and autumn 2014 (Table 3.2), which was almost entirely due to clonal propagation from existing established docks. There was no evidence that the recruitment of newly emerging seedlings made a substantial contribution to this increase; dock numbers were relatively static from autumn 2010 to spring 2013. Furthermore, there was a strong correlation (R^2 = 0.81; P<0.001) between the number of docks present in each treatment in autumn 2014 and spring 2013 (Equation 1); the increase in dock numbers was proportional to the pre-existing population, which indicates clonal reproduction. The clonal process of dock rootstocks creating new growing points and fragmenting over time has been described by Pino et al. (1995). In the present study it was apparent that a relatively homogenous age group of dock seedlings became established during autumn/winter 2009/2010 as described above. It was the remnants of this founding population (after seedling mortality and mortality due to herbicide treatment) that went on to propagate additional ramets when they were approximately 3.5 to 4.5 years of age. In the untreated control there was over a three-fold increase in dock numbers between spring 2013 and autumn 2014. This increase might have been influenced to a very minor extent by the resurrection of some of the docks in the EGH treatments (see below). It is possible the slow-down in growth in dock numbers during 2014 might be due to the mortality of the older (five-year old) ramets balancing clonal recruitment causing the population to approach equilibrium as suggested by Cavers and Harper (1964).

3.4.2. Herbicide treatments

In terms of lowering dock numbers, the NLH were far more effective than the EGH (Table 3.2). Within the NLH Doxstar-NLH was most effective and Alistell was least effective. All of the herbicides used in this experiment were classified by the manufacturers as contact acting via the dock foliage with little or no residual activity and no residual activity of any herbicide was detected in the present study. Within the EGH, Forefront was most effective, and Eagle was least effective, with dock numbers in the latter treatment not different from the untreated control in autumn 2014. There was general agreement between the effectiveness of the EGH in terms of lowering dock numbers and in lowering the subsequent production of root and herbage DM of the marked docks and in the capacity for resurrection of ramets that were ‘apparently dead’ i.e., no dock herbage visibly growing at the soil surface (Table 3.4).

The reason for marking the docks in the EGH treatments and the untreated control was to discern whether changes in dock numbers following the application of EGH was influenced by the resurrection of ramets that were ‘apparently dead’ i.e. no dock herbage visibly growing at the soil surface. There is clear evidence that this was the case across all the EGH (Table 3.3). Although there was no visible above-ground herbage for many of the marked docks for varying intervals of time (up to one year; Table 3.3) there was subsequently a resumption of herbage growth probably from meristematic tissue in the crown of the ‘apparently dead’ root material at some stage within the first year following the application of EGH. There is a small possibility that some of the increase in dock numbers attributed to clonal propagation described above might be partly due to resurrection in the EGH treatments. However, the evidence suggests that post-EGH resurrection of marked docks was more-or-less completed by spring 2013 (Table 3.3) whereas the main surge in clonal prorogation across all treatments was from spring 2013 onwards (Table 3.2).

There was no evidence of a similar recovery of dock numbers following the application of NLH; dock numbers in the NLH tended to decline following the application in spring 2010 until the autumn 2012 prior to the resurgence in numbers by clonal propagation between spring 2013 and the end of this present study.

3.4.3. Herbage production

The application of EGH lowered total herbage production in the year of application (2012) and this was not only due to a decrease in dock herbage; the EGH, particularly Prospect SX, also decreased grass herbage production (Table 3.5). It is commonly alleged by grassland farmers that herbicides for dock control in established grassland, and Prospect SX in particular, can lower grass production although we could find no supporting evidence in the scientific literature similar to that in the present study. Herbage production was not measured in 2010 and, hence, we do not know whether any of the NLH also had a negative impact on grass production.

The most effective herbicide in terms of lowering dock numbers (Doxstar-NLH) also had the highest grass herbage DM yields in 2014, with higher ($P<0.01$) grass production than all the EGH except Prospect SX, and Alistell (NLH). Lowest grass herbage yields in 2014 were in the untreated control, which also had highest dock herbage DM yields of all the treatments. Hence, the highly significant and strong correlation between grass and dock herbage DM yields in 2014 (Equation 2); the suppression of grass by dock herbage in the present study was similar to that recorded Courtney (1985) and Oswald and Haggar (1976). This is in sharp contrast with the earlier years of the present study and 2013, in particular, when there was no difference in grass herbage between the treatments and no relationship between dock and grass herbage DM production. It is clear that herbage production in 2014 was influenced by the large increase in dock numbers due to clonal propagation between the spring of 2013 and autumn 2014. This might also explain why Hopkins and Johnson (2002) and Courtney (1985) reported a similar strengthening inverse correlation between dock and grass herbage production over time.

3.4.4. Eco-efficient herbicide use

The evidence from the present study is that dock seedlings were predominantly recruited during grassland establishment and once the sward canopy had closed there was a decline and stagnation of the dock population density. The secondary surge in population density commenced between three and a half and four years after sward establishment and was predominantly by clonal propagation of existing rootstocks. It was at this stage that the extent of the dock infestation had visibly reached a point that would be considered a problem from a farmer's perspective in terms of numbers of ramets and of the size of individual ramets and, hence, competitiveness with the grass component of the sward. It was in the fifth year (2014) following grassland establishment that the docks significantly suppressed grass production. The conundrum from a farm management perspective is that the extent of problem caused by dock infestation of newly established grassland can often go unnoticed in new leys and only became apparent long after the best opportunity for effectively controlling the infestation using herbicides (i.e., NLH) had passed. Under such circumstances a farmer is likely to adopt the less efficient EGH. Poor rates of control of mature docks similar to that recorded in the present study can often entail repeated applications of herbicides (Savory and Soper 1973, Oswald and Haggar, 1983; Mitchel, 2001; Hopkins and Johnson 2003; Creighton *et al*., 2010) or necessitate sward renovation, both of which entail increased use of herbicides and economic costs.

Not only was the NLH more effective at eliminating docks and increasing grass production, this was achieved with lower application rates of herbicide. This is most straightforwardly evidenced by Doxstar applied at a rate 1.5 L ha^{-1} as an NLH and at a rate of 3.0 L ha^{-1} as an EGH (Table 3.1). At the end of this study in autumn 2014 Doxstar-NLH treatment had a dock population density of 0.09 of that of the untreated control compared with Doxstar-EGH, which had a dock population density of 0.67 of the untreated control. The application of NLH for dock control in grassland is strongly recommended in terms of making eco-efficient use of herbicides. Further research is needed to elucidate the mechanism underpinning the increase in dock numbers recorded during the fourth and fifth year after establishment in the present study. Further research is also needed to determine the appropriate threshold dock population in newly established leys that needs to be exceeded to justify the application of NLH.

3.5. Conclusions

The present study was over a longer timeframe than many similar studies. It showed that docks were much more vulnerable to herbicides as seedlings than as individuals that were well established and around two years of age. The application of NLH gave more effective and enduring control. In each of the EGH there was a resurrection of at least some of the docks that were ‘apparently dead’ following the application of EGH. The extent of this resurgence was proportional to efficacy of the EGH for dock control; the EGH that lowered dock numbers the most initially after application still had the lowest numbers at the end of the study. Across all treatments dock numbers remained relatively low until the fourth year during which there was more than a three-fold increase in numbers due to clonal propagation. Higher numbers and higher dock herbage production substantially lowered grass herbage production in the final year of the study. The results clearly show that controlling docks at the seedling stage is far more environmentally efficient and cost effective than trying to control mature ramets in established grassland.

Chapter 4 The influence of soil potassium status on the productivity of docks (*Rumex obtusifolius* L.) in intensively managed temperate grassland

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Abstract

Docks are a widespread problem in grassland, necessitating novel management solutions as pesticides become increasingly regulated. The objective was to investigate the role of soil test Potassium (K) concentrations (Morgan's solution; Na acetate + acetic acid, pH 4.8; STK) on competitiveness of docks in grassland. The experimental site (52°21N, 7°18W) was reseeded with perennial ryegrass in October 2009. A plot experiment was laid down in a randomized complete block design with seven rates of fertilizer K (0, 50, 100, 150, 200, 250 and 300 kg ha^{-1}) and eight replicates. Dock numbers were measured over six years (2010–2015) and herbage production over five years (2012–2016). There was poor alignment between fertilizer K and STK in the early years of the study, however this alignment improved over time. While fertilizer K had no effect on dock numbers, there were positive correlations between STK early in the study and dock numbers m^{-2} throughout the study. Dock numbers m^{-2} were relatively static between 2010 and 2012 and increased substantially between 2013 and 2015. Between 2013 and 2016 there were strong inverse relationships ($r > -0.765$; $P<0.001$) between dock and grass herbage production. Towards the end of the study the lower annual fertilizer K inputs (0 and 50 kg ha^{-1}) resulted in lower ($P<0.01$) dock root and herbage production with an associated increase ($P<0.05$) in grass herbage production. It is evident there is a threshold STK for permanent grassland infested with docks at which grass is more competitive for plant-available soil K than the docks to the detriment of the dock component of the sward.

Keywords: Docks, Rumex obtusifolius, Grassland, Potassium, Fertiliser

4.1. Introduction

Broad-leaved dock (Rumex obtusifolius L.) hereafter described as 'dock' or 'docks' is an ubiquitous forb of intensively managed temperate grassland in Ireland and elsewhere (Courtney, 1985; Hopkins & Peel; 1985; Harrington *et al.*, 2014). It is widely believed that low levels of docks are relatively harmless in grassland (Hopkins & Johnson, 2002) and may even confer some benefits to grazing ruminants such as reducing the incidence of bloat (Waghorn and Jones, 1989). Nevertheless, abundant populations can affect grassland productivity and the performance of grazing livestock (Courtney & Johnston, 1978; Oswald and Haggar, 1983; McGhie *et al.*, 1983; Hopkins & Johnson, 2002; O'

Donovan *et al.*, 2021). Once established, docks produce a deep taproot and crown structure which acts partly as a reserve supporting herbage growth after defoliation and can give rise to new dock plants through clonal reproduction (Niggli *et al.*, 1993; Pino *et al.*, 1995; Hopkins & Johnson, 2002; Stilmant *et al.*, 2010). Intensive grassland management practices, common on dairy farms, such as high inputs of synthetic fertilisers, land spreading of organic manures and grass-silage production have all been associated with greater abundance of docks (Hopkins and Peel, 1985; Humphreys *et al.*, 1997).

Farmers typically apply herbicides to control docks and maximize grass dry matter (DM) production (Savory and Soper 1973; Haggar, 1980; Oswald & Hagger, 1983; Creighton *et al.*, 2011). However, docks (especially ones emanating from mature root systems) can recover from herbicide applications thus requiring repeated herbicide applications to achieve satisfactory control (Mitchel, 2001; Hopkins & Johnson 2003; O' Donovan *et al.*, 2021). Non-herbicide methods for controlling docks are not widely practiced on farms. Such practices include targeting the dock roots (van Evert *et al.*, 2011; Latsch *et al.*, 2016) or targeting dock herbage (Stilmant *et al.*, 2010; Hejcman *et al.*, 2014) and are not sufficiently fast-acting or cost effective compared with herbicides. However, European Union (EU) legislation such as the Sustainable Use of Pesticides Directive (SUD; Anon, 2009) promotes the use of Integrated Pest Management (IPM) as a core principle to replace or at least reduce pesticide use in agriculture. Furthermore, the more recent EU Farm to Fork Strategy has placed empirical limits on the future use of pesticides in agriculture within the EU (Anon, 2020), all of which hastens the need to explore novel non-chemical dock management approaches.

Zaller (2004) highlighted certain farm management factors that may influence the abundance of docks in grassland, one of which was soil fertility. High application levels of fertilizer N have been widely associated with high incidences of docks in grassland (Chancellor, 1970; Haggar, 1980; Peel & Hopkins, 1980; Courtney, 1985). There is some disagreement in the literature about the influence of soil K on the abundance of docks. Peel and Hopkins (1980) found that docks were common on soils deficient in K but rich in Phosphorous (P). The latter authors stated that this result could have been coincidence as the fields with high levels of docks tended to be silage fields, which often have relatively low soil K concentrations. Humphreys *et al.* (1999) found significant correlations between soil K concentrations and abundance of docks in permanent grassland. This was based on field surveys and substantiated with a pot experiment. Conversely, Van Eekeren *et al.* (2006) found that increasing soil K status under docks grown with grass and clover did not affect the number of docks or dock root biomass in a 2-year pot experiment. Likewise, in a 3-year study, Strnad *et al.* (2010) found that fertilizer K had no effect on the number of docks or on dock root regeneration capacity after cutting the roots immediately beneath the soil surface. As part of the same series of experiments, Strnad *et al.* (2012) found that fertilizer K had little effect on dock biomass production. On the other hand, Hrdlickova *et al.* (2011) found a relationship between dock seed germination and the K status of the mother plants. Furthermore, in New Zealand Harrington *et al.* (2014) found a significant but relatively weak positive correlation between soil K status and dock population density in grassland.

The primary objective of this study was to investigate the impact of increasing fertilizer K input on dock ramet numbers m^{-2}, dock herbage biomass yield, dock root biomass yield and on grass herbage yields. The secondary objective was to use this information to help develop integrated weed management strategies for controlling docks in grassland. Our hypotheses were that increasing fertilizer K input would increase dock numbers, dock herbage production and dock root production in permanent grassland.

4.2. Materials and Methods

4.2.1. Experiment site

This experiment was conducted between September 2009 and September 2016. The soil at the experimental site (52°35N, 7°31W and 20m ASL) was classified as a gleyed brown earth with 20% clay in the surface layer making it an imperfectly drained soil (Collins & Verling, 1976). The experimental area had previously been cropped under an intensive arable six-course rotation including wheat, barley, oats and maize. In October 2009, the field was ploughed to 20 cm, cultivated with a power-harrow, and fertilized with 370 kg ha^{-1} of a compound fertiliser containing 10% N, 10% P and 20% K. The field was then sown with perennial ryegrass (*Lolium perenne* L.); cv. Tyrella, a late flowering diploid and Bealey, a late flowering tetraploid, at a seeding rate of 35 kg ha^{-1}. In November 2009, dock seedling numbers were assessed for population density and spatial homogeneity using a $0.25m^2$ quadrant, placed twenty times randomly along 10 by 100 m length transects across the entire experimental site. *R. obtusifolius* L. was identified according to Farragher (1996). It was the predominant dock species in the sward. There were very low abundance of R. crispus and hybrids between these two species.

The monthly mean rainfall and temperature during the experiment are presented in Figure 4.1. The soil at the experimental area was sampled in spring 2010 and results showed that the soil pH was 6.3 and soil P and K concentrations were adequate according to soil test results (6.8 and 121 mg L^{-1}, respectively) following extraction using Morgan's solution (Na acetate + acetic acid, pH 4.8). To put these concentrations in context, no agronomic response is expected to soil Morgan's P >8.0 mg L−1 and soil Morgan's potassium >150 mg L^{-1} (Coulter *et al.*, 2008; Wall and Plunkett, 2020). Each year the experimental area received fertilization rates of 250 kg ha^{-1} of N and 40 kg ha^{-1} of P. Ground limestone was applied at a rate of 5 t ha^{-1} in spring 2013 in line with soil test results.

4.2.2. Experimental design and treatments

Plots (10 m x 5 m) were delineated in November 2009. The experiment was a randomized complete block design with eight replicated blocks. There were seven plots per block. A 50 cm wide uncropped area delineated each plot to prevent fertiliser being applied inadvertently to adjacent plots. This uncropped area was maintained by an annual application of glyphosate (Roundup Max; Monsanto). The fertilizer K treatments (0, 50, 100, 150, 200, 250 and 300 kg K ha^{-1}) were randomly assigned to plots within each block. Fertilizer K (potassium chloride granules) were applied to each plot by hand in the spring of each experimental year.

4.2.3. Experimental measurements

Dock population densities

Assessments of dock ramet density were made in the spring (March) and autumn (September) of each year between 2010 and 2015 inclusive and are presented as yearly means. For the assessments in 2010 and 2011, when the individual dock plants were quite small, a 0.25 m^2 quadrant was laid down at random 10 times in each plot and the number of dock ramets counted within the quadrant and expressed as average number of docks m^{-2}. For subsequent assessments (2012 to 2015), the total number of visible dock ramets was counted in each plot and expressed as docks m^{-2}. A dock ramet was defined as having at least four leaves arising from one shoot according to Humphreys *et al.* (1999). Detailed assessments were made of selected dock ramets to validate the whole plot assessments.

Herbage Yields

The experimental area was grazed by dairy cows in March each year and subsequently closed for silage. First-cut silage was harvested in late May. A second cut of grass for silage was harvested in July. Subsequently, the experimental area was grazed rotationally by dairy cows until the end of October in line with typical grassland management. Prior to harvesting each silage cut the herbage on each plot was harvested using a Haldrup plot harvester (J. Haldrup, Lùgstùr, Denmark) on 21 May and 30 July 2012, 24 May and 10 July 2013, 22 May and 23 July 2014, 26 May and 28 July 2015 and 26 May and 14 July 2016. Herbage was harvested from a 10 m long by 1.5 m wide strip along the centre of each plot and weighted to determine fresh weight per plot. A subsample of 300 g of fresh herbage was taken from each plot and weighed before and after drying at 105°C for 16 hours in a forced draft oven to determine DM content. The herbage from a second set of subsamples (approximately 1000g) from each plot were separated by hand into dock and other herbage before drying at 105°C for 16 hours in a forced draft oven to determine the relative proportions of docks and other herbage (predominantly perennial ryegrass and other unsown grass species) on a DM basis.

Dock root biomass

In January 2015 10 dock ramets were selected at random per plot and carefully dug out by hand. Roots were excavated to a depth of at least 50 cm. Only dock roots physically attached to the dock ramet crown were assessed and weighed. The root of each dock was carefully separated from the shoot component in the laboratory by cutting each crown at the lowest leaf scar. The roots were washed and both roots and shoots were dried to a constant weight at 105 ^{0}C in a forced draft oven to determine DM weight.

Soil analyses

In January of each year between 2011 and 2015 the soil in each plot was sampled by taking 20 soil cores to a depth of 10 cm. The K and P concentrations and soil pH were determined as described above.

4.2.4. Statistical analysis

Soil test K concentrations (STK) per plot in each of five years were subjected to a two-factor (potassium fertilizer x year) ANOVA examining the main effects of each factor and interactions between factors, with eight replicates. Dock ramet numbers per plot averaged for each assessment date per year for each of six years were transformed using a natural log (y=log(x+1)) and subjected ANOVA examining the effect of the potassium fertilizer treatments within each year, with eight replicates. Dock ramet numbers per plot at the start of the experiment (spring 2010) were used as a covariate in this analysis. All statements of significance are based on the transformed values. Untransformed data are presented in Table 4.1 to aid clarity. Grass herbage DM yields were each summed for each year (2012, 2013, 2014, 2015 and 2016) and subjected to a two-factor (potassium fertilizer x year) ANOVA. Likewise for dock herbage DM and total (grass and dock) herbage yields were similarly subjected to ANOVA. Excavated docks and herbage and root weights were subjected ANOVA examining the effect of the potassium fertilizer treatments, with eight replicates. The relationships between fertiliser K treatments and (i) STK per plot, (ii) dock numbers per plot, (iii) annual dock herbage dry matter production per plot and (iv) annual grass herbage dry matter production per plot (v) dock root production per plot in 2015 and (vi) dock herbage and root production per plot in 2015 were examined using linear regression to calculate correlation coefficients (r). Likewise, the relationships between STK per plot and (i) dock numbers per plot, (ii) annual dock herbage dry matter production per plot and (iii) annual grass herbage dry matter production per plot (iv) dock root production per plot in 2015 and (v) dock herbage and root production per plot in 2015 were examined using linear regression. Likewise, correlation coefficients between dock herbage production per plot and grass herbage production per plot were calculated within each year between 2012 and 2016. Finally, the relationships between dock numbers per plot in each year and (i) dock numbers per plot in subsequent years, (ii) dock herbage production per plot and

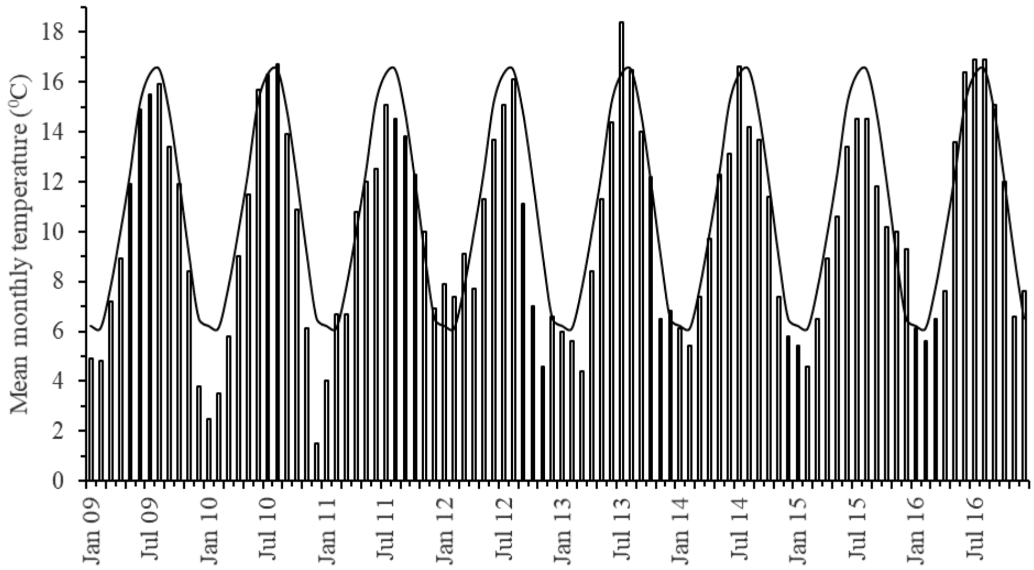
(iii) grass herbage production per plot were examined using linear regression. The software package MSTAT was used for statistical analysis.

4.3. Results

4.3.1. Meteorological data

Meteorological data was obtained from a Met Eireann (www.met.ie) weather station approx. 800 m from the experimental site. The mean annual air temperature was lower in each of the seven years of this study than the previous ten-year average (11°C). The winters of 2009/2010 and 2010/2011 were exceptionally cold (Figure 4.1). The annual rainfall amounts each year were similar to the ten-year average (1073 mm). The rainfall during November 2009 was twice normal and there was exceptionally high rainfall during the months of June and August 2012 and in December 2015. Rainfall in December 2015 was almost five times the 10-year average rainfall for December.

(a)



(b)

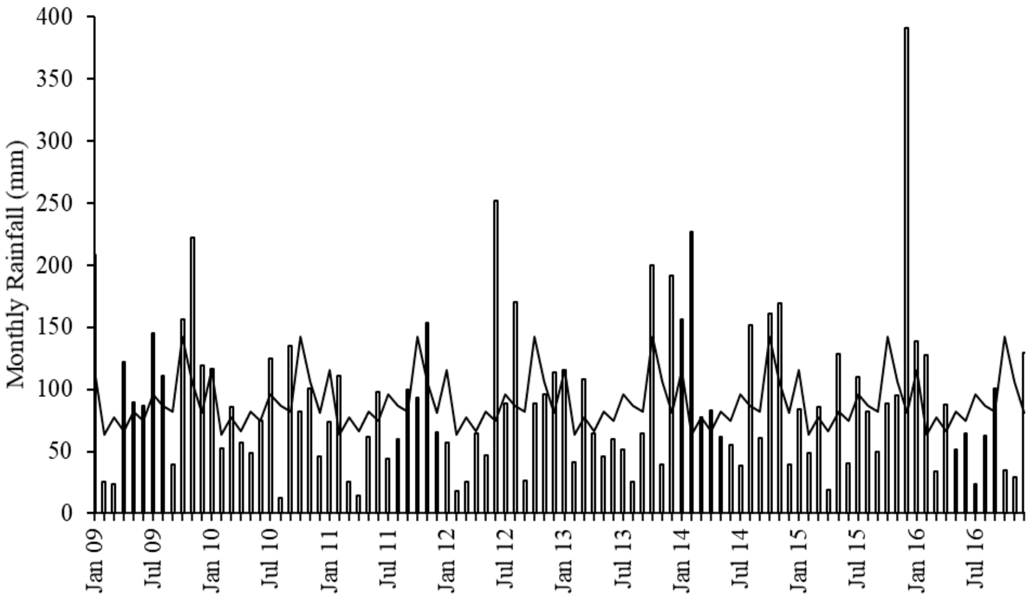


Figure 4.1. Monthly air temperature (a) and monthly rainfall (b) at the experimental site between 2009 and 2016. The columns show the levels during the experiment and the lines show the lines show the averages of the previous 10 years

4.3.2. Fertiliser K and soil test K (STK)

Where no fertiliser K was applied, STK declined ($P<0.001$) during this study (Table 4.1). Likewise with annual input of 50 kg ha^{-1} STK also tended to decline. With annual input of 100 kg ha^{-1} the STK remained close to the baseline STK measured during the winter 2009 (121 mg L^{-1}) although it tended to decline between January 2011 and January 2012 and subsequently increase between January 2013 and January 2014. Likewise with annual input of 150 kg ha^{-1} STK tended to decline initially and subsequently increase in 2014 and 2015 to concentrations higher than the baseline STK (Table 4.1). With the higher rates of fertiliser K input (≥200 kg ha^{-1}) STK increased year-on-year roughly in line with increasing annual fertiliser K inputs.

The correlation coefficient for the relationship between annual fertiliser K input and STK increased year-on-year during the study from $r = 0.433$; $P<0.01$ in 2011 to $r = 0.905$; $P<0.001$ in 2015 (Table 4.3). Likewise, the correlation coefficients between STK concentrations in successive years increased over time (Table 4.4).

Table 4.1. Annual Fertiliser K input and soil K concentrations in each of five years

	Fertiliser K (kg ha^{-1})						
	0	50	100	150	200	250	300
Year	Soil K concentration (mg L^{-1})						
2011	109	110	123	119	136	149	154
2012	89	75	101	105	121	131	165
2013	85	90	101	103	140	195	192
2014	66	101	138	200	220	276	338
2015	63	75	127	164	216	275	308
	Year	Fertiliser K			Year x fertiliser K		
SEM	7.3***	5.7***			12.7***		

***P<0.001;

4.3.3. Dock Numbers

Dock numbers m^{-2} (mean of the March and September assessments) remained more-or-less the same across treatments in 2011, 2012 and 2013 with a big increase in dock numbers between 2013 and 2014 and a smaller increase in numbers m^{-2} between 2014 and 2015 (Table 4.2). Fertiliser K applications had no effect on dock numbers m^{-2} in each of the years during this study (Table 4.2 and Table 4.4). On the other hand, there were positive correlation coefficients between STK in January 2011 and dock numbers m^{-2} in individual plots throughout the study (Table 4.4). The relationship between STK and dock numbers m^{-2} tended to progressively weaken over time and was not significant (P>0.05) in 2014 and 2015.

Table 4.2. Annual Fertiliser K input and dock numbers throughout the study

	Fertiliser K (kg ha^{-1})							
	0	50	100	150	200	250	300	SEM
Year	Dock numbers (m^{-2})							
2011	5.7	5.9	7.8	5.8	6.7	7.0	5.4	1.26^{NS}
2012	6.4	6.6	8.1	6.5	7.2	7.9	5.8	1.26^{NS}
2013	6.4	6.5	7.8	6.2	7.6	8.2	6.1	1.15^{NS}
2014	10.2	11.4	13.0	10.3	12.9	13.3	10.6	1.71^{NS}
2015	11.4	12.9	15.2	13.0	14.8	15.4	13.0	2.11^{NS}
Mean	7.7	8.1	9.8	8.0	9.5	9.5	7.7	

^{NS}Not significant

4.3.4. Dock and grass herbage production

Annual fertilizer K input had no (P>0.05) effect on dock herbage DM production (two silage harvests combined) within each of the years between 2012 and 2015 (Table 4.5). In 2016 the two lowest K fertilizer treatments (0 and 50 kg ha^{-1}) had lower (P<0.05) dock herbage DM production than any of other fertilizer K treatments (Table 4.5). Likewise annual fertilizer K input had no (P>0.05) effect on grass herbage DM production in each of the years between 2012 and 2015. In contrast to dock herbage in 2016, there tended to be higher grass herbage production on the two lowest K fertilizer treatments compared with grass herbage production in each of the other fertilizer K treatments, which were not different from each other (Table 4.5).

In general relationships between STK and dock herbage production within each year tended to be weak or not significant (data not presented). Likewise, there were no significant relationships between STK and grass herbage production within years (data not presented). Within each year between 2013 and 2016, there were strong negative correlations (P<0.001) between dock herbage DM and grass herbage DM (Table 4.6).

Dock root DM

Dock root DM increased (P<0.01) with increasing annual fertiliser K input from 4.67 t ha^{-1} for 0 kg ha^{-1} to 8.52 t ha^{-1} for 300 kg ha^{-1} (Table 4.5). Likewise, the combination of dock herbage and root production in 2015 increased (P<0.01) with annual fertiliser K input (Table 4.5). There was also a positive correlation (r = 0.352; P<0.01) between annual fertiliser K input and dock root DM production (results not presented). Furthermore, there were positive correlations (P<0.001) between STK in each year between 2011 and 2015 and dock root DM production in 2015 (Table 4.4).

Table 4.3. Correlation coefficients (r) between annual input of fertilizer K and soil test K concentrations (STK) in each year between 2011 and 2015

Fertilizer K ($kg\ ha^{-1}$)	STK ($mg\ L^{-1}$)
2011	0.433**
2012	0.630***
2013	0.706***
2014	0.905***
2015	0.905***

**P<0.01; ***P<0.001

Table 4.4 Correlation coefficients (r) between soil K concentrations each year and (i) soil K concentrations in the following year, (ii) dock numbers, (iii) dock root DM in 2015 and (iv) dock herbage and root DM in 2015

	STK (mg L^{-1})				
STK (mg L^{-1})	2011	2012	2013	2014	2015
2011					
2012	0.582***				
2013		0.729***			
2014			0.784***		
2015				0.925***	
Dock Numbers					
2011	0.392**				
2012		0.308*			
2013			0.318*		
2014				NS	
2015					NS
Dock Root DM (t ha^{-1})	0.590***	0.530***	0.501***	0.505***	0.486***
Dock herbage and root DM (t ha^{-1})	0.642***	0.534***	0.488***	0.509***	0.487***

*P <0.05; **P<0.01; ***P<0.001; NSNot significant;

Table 4.5. The effect of potassium (K) fertilisation on dock and grass dry matter (DM) herbage yields from a two-cut silage system over five years (2012 to 2016 inclusive) and on dock root yields in January 2015 and dock herbage yields and root yield in 2015

	Fertiliser K (kg ha^{-1})							
	0	50	100	150	200	250	300	SEM
Year	Dock herbage DM (t ha^{-1})							
2012	0.40	0.32	0.43	0.30	0.57	0.57	0.50	0.098^{NS}
2013	1.86	1.66	1.68	1.31	1.68	2.44	1.53	0.296^{NS}
2014	3.81	4.41	4.50	3.42	4.00	4.90	3.92	0.427^{NS}
2015	3.22	3.82	5.07	4.00	4.39	4.68	3.82	0.310^{NS}
2016	3.61^{b}	3.33^{b}	5.16^{a}	4.82^{a}	5.49^{a}	4.94^{a}	4.79^{a}	0.327*
Mean	2.58	2.71	3.37	2.77	3.27	3.51	2.91	0.162^{NS}
	Grass herbage DM (t ha^{-1})							
2012	7.37	7.32	7.43	7.43	7.42	7.41	7.38	0.171^{NS}
2013	7.56	7.94	7.93	7.93	8.20	7.48	8.41	0.334^{NS}
2014	6.50	7.31	6.62	7.77	7.06	5.96	7.22	0.459^{NS}
2015	5.99	6.23	5.07	5.98	5.46	4.97	6.15	0.380^{NS}
2016	7.49^{a}	7.30^{a}	5.73^{b}	5.55^{b}	5.06^{b}	6.33^{ab}	5.91^{b}	0.434*
Mean	6.98	7.22	6.55	6.93	6.64	6.43	7.01	0.188^{NS}
	Dock root DM (t ha^{-1})							
2015	4.67^{c}	6.28^{abc}	6.98^{ab}	5.47^{bc}	7.61^{ab}	7.94^{a}	8.52^{a}	0.735**
	Dock herbage and root DM (t ha^{-1})							
2015	8.28^{d}	9.61^{cd}	12.15^{abc}	10.29^{bcd}	13.11^{a}	12.88^{ab}	13.31^{a}	0.875**

*P<0.05; **P<0.01; ^{NS}Not significant

Means within rows with the same superscripts are not (P>0.05) different from each other according to Dunacan's multiple range test

4.3.5. Dock numbers and dock and grass herbage production

In general, there were close correlations (>0.87; P<0.001) between dock numbers m^{-2} in successive years (Table 4.7). Throughout the study there were positive correlations between dock numbers and dock herbage production in each year and these correlations tended to strengthen over time (Table 4.7). There were negative correlations between dock numbers and grass herbage production and these correlations also tended to strengthen over time (Table 4.7). In terms of total herbage production there tended to be weak (<0.43) positive or non-significant correlations between dock numbers and total herbage production in 2012 and 2013 (results not presented). In contrast there tended to be weak (<0.33) negative or non-significant correlations between dock numbers and total herbage production in 2015 and 2016 (results not presented).

Table 4.6. Correlation coefficients (r) between annual dock herbage dry matter production and annual grass herbage dry matter production for each year between 2012 and 2016

	Dock herbage (kg ha^{-1})				
	2012	2013	2014	2015	2016
Grass herbage (kg ha^{-1})					
2012	^{NS}				
2013		-0.765***			
2014			-0.930***		
2015				-0.924***	
2016					-0.872***

***P<0.001; ^{NS}Not significant.

Table 4.7. Correlation coefficients (r) between the number of docks at different stages of this study and (i) subsequent dock numbers, (ii) annual dock herbage dry matter production and (iii) annual grass herbage dry matter production between 2012 and 2015

	Dock Numbers (m^{-2})				
	2011	2012	2013	2014	2015
Dock Numbers (m^{-2})					
2010	0.889***				
2011		0.896***			
2012			0.872***		
2013				0.934***	
2014					0.936***
Dock herbage (kg ha^{-1})					
2012		0.420***			
2013			0.787***		
2014				0.788***	
2015					0.844***
Grass herbage (kg ha^{-1})					
2012		NS			
2013			-0.523***		
2014				-0.767***	
2015					-0.813***

*P <0.05; **P<0.01; ***P<0.001; NS Not significant

4.4. Discussion

4.4.1. Fertiliser K and STK

The results were not as clear cut as anticipated by the design of this experiment mainly because plant-available soil K (represented by STK) in the earlier years of this study did not closely align the fertilizer K treatments imposed (Tables 4.2 and 4.3). This alignment improved over time during the study with correlation coefficients increasing from 0.433 ($P<0.01$) in 2011 to 0.905 ($P<0.001$) in 2014 and 2015 (Table 4.3). This soil is not known to be K-fixing and it is clear that the soil at this particular site had considerable capacity to maintain STK levels under conditions with no or low fertilizer K inputs and where there were high offtakes of K in herbage (two harvests of silage) per year in each year between 2010 and 2016. To put the STK results in Table 4.2 in context: <50 mg L^{-1} is classified as critically deficient for grassland; 50 to 100 mg L-1 is moderately deficient; 100 to 150 mg L^{-1} is the target range requiring maintenance K inputs and >150 mg L^{-1} is classified as not needing additional K inputs (Wall and Plunkett, 2020). Hence, after seven years of two-cut silage management along with grazing in spring and autumn, the STK levels in 2015 under the zero fertilizer K input remained above the critical minimum soil K level for agricultural production (50 mg L^{-1}; Wall & Plunkett, 2020). On average during the study approximately 9.9 t ha^{-1} of herbage DM was harvested per year as two-cut silage (Table 4.5). Assuming an average of 25 g kg^{-1} of K in herbage DM (Humphreys *et al.*, 1999) this equates to average annual K offtake of 245 kg ha^{-1}. Nevertheless, under very high annual fertilizer K input (>150 kg ha^{-1}) STK concentrations increased progressively during the study (Table 4.2). These changes in STK culminated in the fertilizer K treatments having significant ($P<0.05$) effects on both dock and grass herbage production in 2016 (Table 4.5).

4.4.2. Dock numbers

Another somewhat problematical aspect of the design of this experiment was the reliance on the natural abundance of dock seeds in the soil to generate the initial population of dock seedlings. The density of the population of seedlings tended to be variable across the site. This was somewhat mitigated by the relatively large number of replicated blocks (n = 8) in the experimental design. Nevertheless, there was no

(P>0.05) difference in the number of dock ramets per fertilizer K treatment within any of the years in this study (Table 4.1). There was also a considerable increase in dock numbers m^{-2} in all the fertilizer K input treatments during the study particularly between 2013 and 2014 with a further increase between 2014 and 2015 (Table 4.1). A similar increase in dock numbers m^{-2} was recorded by O' Donovan *et al.* (2021) and, similar to the present study, was attributed to clonal propagation.

Similar to the ANOVA there was no (P>0.05) correlation between fertilizer K input and dock numbers throughout the study (results not presented). On the other hand, there were positive correlations between STK and dock numbers m^{-2} in the earlier years of this study (Table 4.4). This indicates that STK levels had a greater influence on dock numbers m^{-2} early rather than later in the experiment, perhaps soon after initial establishment. Subsequent dock numbers m^{-2} were closely correlated with the initial established population densities throughout this study with correlation coefficients generally >0.87 (P<0.001; Table 4.7). However, as the fertilizer K treatments had an increasing influence on STK over time during the experiment (Table 4.3), STK changed to the extent that it was no longer (P>0.05) correlated with dock numbers m^{-2} (Tables 4.2 and 4.4). This supports the contention that STK influenced dock numbers m^{-2} early rather than later in their development. These results also indicate that fertilizer K input and STK had no detectible impact on the extent of clonal reproduction by the dock ramets in 2014 and 2015 (Tables 4.1 and 4.4).

4.4.3. Biomass production

The grass herbage production response to fertilizer K in 2016 was not a typical 'increasing at a diminishing rate (for example Keady and O 'Kiely, 1998) response curve to fertilizer input: Grass herbage production in 2016 was higher under zero and 50 kg ha^{-1} of fertilizer K input than under higher fertilizer K input (Table 4.5). This atypical grass herbage production response was due to interaction between the dock and grass components of the swards. There was lower (P<0.05) dock herbage production in 2016 under zero and 50 kg ha^{-1} of fertilizer K input and this coincided with higher (P<0.05) grass herbage production compared with the higher fertilizer K input treatments. Furthermore, dock root DM production harvested in 2015 increased (P<0.01) with increasing fertilizer K input and likewise for combined dock herbage and root DM production in 2015 (Table 4.5). The results of this study clearly show that plant- available soil K is a key nutrient for dock root biomass production, which is important bearing in mind that the dock root comprised the greater part of the total dry matter of individual dock ramets (an average of 59% in Table 4.5). Many authors (Niggli *et al.*, 1993; Hopkins and Johnson, 2002 and Van Evert *et al.*, 2020) demonstrated that docks mobilise their root reserves to boost their foliar re-growth and out-compete grass after defoliation.

There was no significant difference between the fertilizer K treatments in terms of the total combined dock and grass herbage harvested for silage in 2016 indicating that lower dock herbage production coincided with higher grass herbage production (data not presented). Clearly there was competition between the dock and grass components of the sward; there were strong (>0.76; P<0.001) negative correlations between dock and grass herbage production in 2013 and in each of the subsequent years of the experiment (Table 4.6). This inverse relationship between grass and dock herbage production is in general agreement with many previous studies (Oswald and Hagger, 1983; Courtney, 1985; Hopkins and Johnson, 2002 and O' Donovan *et al.*, 2021). In the present study this competition was influenced by fertilizer K input (Tables 4.5) and STK (Table 4.4). Hence, it seems that STK influenced the competition between docks and grass and that the influence of STK in 2011 on subsequent dock numbers played a role in this interaction. This is supported by the close correlations between dock numbers throughout the experiment and dock herbage production particularly in each year between 2013 and 2016 (Table 4.7).

4.4.4. STK and competition between grass and docks

Humphreys *et al.* (1999) contended that the dense network of grass roots made it more competitive for plant-available soil K (represented by STK) than docks under circumstances of limited plant availability of K in the soil. Hence, there was higher grass DM production at lower STK levels, which is in agreement with the herbage production recorded in the present study in 2016. Under circumstances with higher plant-availability of soil K, the dock component was more productive to the detriment of the grass component of the sward. It is clear that the dock component of the sward became more competitive over time; averaged over the four fertilizer K treatments of between 150 and 300 kg ha^{-1} dock herbage production increased from 0.5 t ha^{-1} in 2012 to 5.0 t ha^{-1} in 2016 (Table 4.5). The largest year-on-year increase in dock herbage production occurred between 2013 and 2014 (Table 4.5), which coincided with the substantial increase in docks m^{-2} within the same timeframe. It is possible that the docks became more competitive in the sward over time because of their greater numbers. It is equally possible that as the docks became better established between 2010 and 2013 and became more competitive in the sward that they had greater resources to allocate towards vegetative reproduction giving rise to more clones. Either way, it is evident that this clonal increase in dock numbers m^{-2} between 2013 and 2014 and between 2014 and 2015 was not influenced by STK.

It seems that STK had a positive impact on the establishment and early development of docks between 2009 and 2011, perhaps favouring establishment and early development in plots with higher STK. This line of reasoning is not contradicted by the fact that docks m^{-2} were not affected by fertilizer K input (Table 4.1) because there was poor alignment between fertilizer K input and STK in the early years of the experiment (Table 4.2). Moreover, it must be borne in mind that the sward was sown in 2009, the first application of fertilizer K to plots was during 2010 and the first measurement of STK was in January 2011. The weight of the evidence for STK influencing dock numbers m^{-2} early in the experiment is not very strong but it is sufficiently strong to merit not being entirely disregarded. There is a need for more research to elucidate this issue.

The results of the present study broadly agrees with that of earlier studies. Humphreys *et al.* (1999) found that competition between grass and docks was most detrimental to dock biomass production under limited STK availability. The converse was not true for high K fertilizer inputs; higher fertilizer K inputs did not increase dock biomass production (Humphreys *et al.*, 1999). In the present study, the impact of fertilizer K input on dock biomass production did not become evident until seven years after sowing the grassland mainly because this was the timeframe necessary for the capacity of the soil to supply plant-available K to decline to the levels of sufficient scarcity that the competition for plant-available soil K between grass and dock was detrimental to the dock plants. A similar scenario might explain the absence of an effect of fertilizer K on dock biomass production recorded by Van Eekeren *et al.* (2006), which was examined within a two-year timeframe. The STK levels in the three-year study conducted by Strnad *et al.* (2010) were described as optimal for crop growth and hence were probably not sufficiently low for competition between grass and docks for STK to be detrimental to dock biomass production. These results are also broadly in agreement with Harrington *et al.* (2014) who found a significant but relatively weak positive correlation between soil K status and dock population density in grassland.

4.5. Conclusions

This study was limited by the poor alignment between fertilizer K input and STK in the early years of this study. Furthermore, there was reliance on natural generation of dock seedlings, which was variable across the experimental site. Nevertheless, alignment between fertilizer K input and STK improved during the seven years encompassed by this experiment. In the final year of the study (2016) the low fertilizer K treatments, and associated lower STK, resulted in a reduction of dock herbage and root biomass production and an associated increase in grass herbage production. It was evident that grass was more competitive for plant-available K at STK levels in the range of 60 to 110 mg L^{-1} (roughly equivalent to index 2 in the Irish system based on the Morgan's test; Wall and Plunkett, 2020) to the extent that dock biomass production was supressed. At higher STK levels dock herbage production accounted for 47% of combined grass and dock herbage production in 2016. There was evidence to suggest that STK in the earlier years of the study has a positive and persistent influence on dock population densities per plot, which is somewhat in agreement with Harrington *et al.* (2014). There was no evidence that higher fertilizer K input and STK influenced dock numbers via clonal propagation.

Chapter 5. Can seedling dock (*Rumex obtusifolius* L.) populations be used to predict long term grass production losses following re-seeding?

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Abstract

Docks are a prolific weed of intensively managed grassland, often present as seedlings after the establishment of grass leys. The objective of this study was to examine the impact of a wide range of dock seedling population densities on the economic value of herbage production over the following seven years and ultimately determine a threshold value of dock seedlings in new leys to avoid economic loss. Eighty grassland plots were established in 2009/10 with dock population densities ranging between 0.1 and 9.9 with a mean number of 3.3 m^{-2}. Docks m^{-2} did not change, and docks had no effect on grass herbage production during the following two years (2011 and 2012). Between 2013 and 2015 there was a 3.4-fold increase in dock m^{-2}, with 90% of the variation in dock m^{-2} in the autumn 2015 was explained by the variation in docks m^{-2} in spring 2013. Also, during this timeframe dock herbage increased from 12.6% to 31.2% of total annual herbage DM production. In each year between 2013 and 2016 there were strong inverse relationships ($r > -0.776$; $P<0.001$) between dock and grass herbage production. Dock m^{-2} in 2010 accounted for 36% of the variation in the economic value of herbage produced from plots between 2012 and 2016. On this basis and taking into account the cost of application of post-emergence herbicide, post emergence herbicide should be applied to avoid population densities >1.0 docks m^{-2} in new leys.

Keywords: Docks, Rumex obtusifolius, Grassland, Herbicide, New ley

5.1. Introduction

Broad-leaved dock (*Rumex obtusifolius* L.) referred to as ‘dock’ or ‘docks’ in this paper is a common weed of intensively managed grassland in Ireland and other temperate regions (Anon, 2006; Hopkins and Johnson, 2002; Zaller, 2004). Intensive grassland management practices such as high inputs of mineral fertilisers, organic manure applications and grass-silage production have all been associated with the abundance of docks (Hopkins and Peel, 1985). Docks become established in grassland because of soil disturbance such as during cultivation for new grass leys, poaching damage or other events that create open patches in the sward (Humphreys *et al.*, 1997). Thus, mature dock populations have been termed ‘a relic’ from past soil disturbance events (Cavers and Harper, 1967). In such soil disturbance scenarios, dock plants can arise from two sources: seed and sections of old rootstocks containing viable meristematic material

(Zaller, 2004). The dock plant has prodigious capacity for reproduction via seeds. This is manifested both in terms of seed production (Hrdličková *et al.*, 2011) and in the capacity of these seeds to remain viable in the soil over a long number of years (Cavers and Harper, 1964). This can result in a substantial seedbank of up to five million seeds per acre in the top 15 cm of soil (Bond *et al.*, 2007).

Where docks arise from old rootstocks, this has been shown to be a significant source of new dock plants in organic farming (Bond *et al.*, 2007). In conventional farming however, the widespread use of glyphosate can effectively eliminate rootstocks as a source of new dock plants during grassland establishment (Anon, 2017; Creighton *et al.*, 2011). Hence, the recruitment of seedling docks is likely to be the primary source of docks in newly established, conventionally managed grassland. There is approx. 75,000 ha of grassland reseeded in Ireland each year (Anon, 2006; Anon, 2019; Casey and Humphreys, 2002) and as reseeding is considered a key management tool for improving the productivity and profitability of intensively managed grassland (Creighton *et al.*, 2011), anything that reduces its effectiveness is of importance.

Seedling docks are known to be very susceptible to natural competition and environmental stress (Hongo, 1989a; Humphreys *et al.*, 1997). It has been shown that dock seedlings can be controlled by measures such as increasing the competition during establishment of a new ley (Keary and Hatcher, 2004; Ringselle *et al.*, 2019), the use herbicides (O'Donovan *et al.*, 2021) or cutting strategies (van Eekeren *et al.*, 2006). However, once established, docks are well adapted to survive and flourish in agricultural grassland and are difficult to control using measures such as defoliation (Niggli, 1993; van Evert *et al.*, 2020), herbicides (Hopkins and Johnson, 2003; O'Donovan *et al*., 2021) and fertiliser (Niggli *et al*., 1993; Hopkins and Johnson, 2002; O'Donovan *et al*., 2022; Strnad *et al*., 2012). Other control strategies targeting the roots with hot water or by digging out the roots have been shown to eliminate docks but are costly to implement particularly for dense dock populations (Latsch *et al*., 2017; Hujerova *et al*., 2016). In fact, the recommendation by Zaller (2004) is that the 'control' of docks should be directed at minimising their seed return to the soil and reducing their regrowth capacity and hence their impact on the grass sward.

The impact of docks on grass herbage production is well known (O'Donovan *et al*., 2021; Chapter 3; Courtney, 1985; Oswald and Haggar, 1983. For example, in Chapter 3, for each increase in dock dry matter (DM) herbage production of 1.00 t ha^{-1} there was a corresponding decrease in grass herbage DM production of 1.05 t ha^{-1} in 2014 and 1.06 t ha^{-1} in 2015. These relationships agree with the general conclusion of earlier work that where docks comprise greater than 10% ground cover of the sward (which is a combination of dock population density and the size of individual docks), they reduce grass DM production in a 1:1 linear relationship (Courtney, 1985; Hopkins and Johnson, 2003; Oswald and Haggar, 1983). Earlier work in this thesis has shown that dock population densities increase substantially during the third and fourth years after establishment in a new ley (O'Donovan *et al*., 2021; Chapter 3). The magnitude of this expansion was directly related to the founding population of docks established in the new ley. Hence, limiting the extent of this population is key to maintaining productive grass swards in the longer term (5 to 10 years after establishment).

A key question is what is an acceptable density of dock seedlings in a new ley that does not require intervention by post-emergence herbicides or other means? Furthermore, a related question is, having deemed it necessary to apply post-emergence herbicide, what level of control is acceptable to avoid repeated applications to achieve an acceptable level of control? Such information is warranted to avoid the unnecessary application of post-emergence herbicide. The answer to these questions can be determined by determining the economic impact of dock population densities in the years that they are most damaging to grass production. These population densities can then be related back to the original founding populations of established docks in the newly sown leys following the application of post-emergence herbicide in instances where post-emergence herbicides have been applied. The dataset for the present study (n = 80) was taken from the two studies described earlier in this thesis. It encompassed the control and the four treatments that received post-emergence herbicide in Chapter 3 (O'Donovan *et al*., 2021) and the five treatments that received adequate K fertilization such that it did not impact on the productivity of the dock component of the sward, i.e. 100, 150, 200, 250 and 300 kg ha^{-1} of fertilizer K each year in Chapter 4 (O'Donovan et al., 2022). Both of these studies were conducted contemporaneously and adjacent to each other at the same site.

The objective of this study was to determine an appropriate threshold dock population in newly established leys that needs to be exceeded to justify the application of post-emergence herbicides. Our hypothesis was that seedling dock numbers in the first year after reseeding can be used to predict grass herbage effects for at least seven years after establishing a new grass ley.

5.2. Materials and Methods

5.2.1. Experimental design

The dataset (n = 80) was comprised of the two earlier studies as described above. This approach was taken to include as wide a range as possible of the number of established docks m^{-2} in new leys in 2010 following the application of post-emergence herbicide to 32 of the 80 plots (10 m x 5 m). Docks were endemic and spatially heterogeneous at this site and following the application of post-emergence herbicide there was a range between 0 and 26 docks m^{-2}.

This study used data from between 2010 and 2016. The soil at the experimental site (52°35N, 7°31W and 20m ASL) was classified as a gleyed brown earth with 20% clay in the surface layer making it an imperfectly drained soil (Collins and Verling, 1976). The site had previously been cropped under intensive arable cropping; wheat, barley, oats and maize grown in a six-course rotation. In October 2009, the field was ploughed to 20 cm, cultivated with a power-harrow and fertilized with 370 kg ha^{-1} of a compound fertiliser containing 10% N, 10% P and 20% K. The field was then sown with perennial ryegrass (*Lolium perenne* L.; cv. Tyrella, a late flowering diploid and Bealey, a late flowering tetraploid) at a seeding rate of 35 kg ha^{-1}. Plots (10 m x 5 m) were delineated in November 2009 as described by O'Donovan *et al*., 2021 and in Chapter 3. Also in November 2009, dock seedlings were identified according to Farragher (1996). *Rumex obtusifolius* L. It was the predominant dock species in the sward. There was a very low abundance of *R. crispus* and hybrids between these two species.

The monthly mean rainfall and temperature during the experiment are presented in Figure 5.1. The soil at the experimental area was sampled in spring 2010 and results showed that the soil pH was 6.3 and soil P and K concentrations were adequate according to soil test results (6.8 and 121 mg L^{-1}, respectively) following extraction using Morgan's solution (Na acetate + acetic acid, pH 4.8). To put these concentrations in context, no agronomic response is expected to soil Morgan's phosphorous (P) >8.0 mg L^{-1} and soil Morgan's potassium (K) >150 mg L^{-1} (Wall and Plunkett, 2020). Each year the experimental area received fertilization rates of 250 kg ha^{-1} of N and 40 kg ha^{-1} of P. Ground limestone was applied at a rate of 5 t ha^{-1} in spring 2013 in line with soil test results.

5.2.2. Experimental measurements

Dock population densities

Whole plot assessments of the numbers of dock ramets were conducted as described by O'Donovan *et al*. (2021). Assessments were made each spring and autumn between autumn 2010 and autumn 2015. Detailed assessments were made of selected dock ramets to validate the whole plot assessments.

Herbage Yields

The experimental area was grazed by dairy cows in March each year and subsequently closed for silage. First-cut silage was harvested in late May. A second cut of grass for silage was harvested in July. Subsequently, the experimental area was grazed rotationally by dairy cows until the end of October in line with typical grassland management. Prior to harvesting each silage cut the herbage on each plot was harvested using a Haldrup plot harvester (J. Haldrup, Lùgstùr, Denmark) on 21 May and 30 July 2012, 24 May and 10 July 2013, 22 May and 23 July 2014, 26 May and 28 July 2015 and 26 May and 14 July 2016. Herbage was harvested from a 10 m long by 1.5 m wide strip along the centre of each plot and weighted to determine fresh weight per plot. A subsample of 300 g of fresh herbage was collected from each plot and weighed before and after drying at 105°C for 16 hours in a forced draft oven to determine DM content. The herbage from a second set of subsamples (approximately 1000g) from each plot were separated by hand into dock and other herbage before drying at 105°C for 16 hours in a forced draft oven to determine the relative proportions of docks and other herbage (predominantly perennial ryegrass and other unsown grass species) on a DM basis.

Assessment of the non-sown species content of plots

In 2016 it was clear that non-sown grass (NSG) species had made considerable inroads into plots. Each plot was visually assessed on a whole plot basis for the presence of Perennial Ryegrass (PRG), which was identified according to Farragher (1996), and NSG species in August 2016. The primary NSG was *Agrostis stolonifera* L. (Farragher, 1996) along with *Poa annua* L. The proportions of PRG and NSG were each multiplied by the grass herbage yield to calculate their individual herbage yields (t DM ha^{-1}) in 2016.

Economic Analysis

The economic value of annual herbage production was calculated on the basis of the estimation that the herbage harvested as silage represented 0.75 of the total herbage production in each year between 2012 and 2016. Furthermore, grass in each year between 2012 and 2015 and PRG in 2016 was valued at €100 t^{-1} DM, bent grass in 2016 was valued at €80 t^{-1} DM and dock herbage in each year between 2012 and 2016 was valued at €65 t^{-1} DM. A standard cost of €60/t of grass DM was included to account for ancillary costs. These were the opportunity cost of land at €50/t of grass DM, grassland renovation (every 20 years) at €7.50/t of grass DM and the application of lime (every five years) at €2.50/t of grass DM (Finneran *et al*. 2011; O'Donovan *et al*. 2011). The cost of fertilizer application, in terms of working time and machinery costs, were costed based on contractor charges of €37/t of fertilizer applied (FCI, 2019). The cost of fertilizer N in the form of urea (46% N and €0.85/kg of N) was based on the average cost between 2008 and 2016 according to the central statistics office (CSO, 2018). A standard cost of K and P was included on the basis that herbage was estimated to contain 3 g/kg DM of P and 25 g/kg DM of K. The cost of fertilizer P was €2.55/kg and of fertilizer K was €0.78/kg based on the average cost of each between 2008 and 2016 (CSO, 2018).

The values for NSG and dock herbage were calculated based on their feeding values relative to PRG. Docks have feeding value approximately 65% of PRG (Courtney, 1985) and therefore dock herbage was valued as €65 per tonne DM of dock herbage. Likewise, NSG such as *A. stolonifera* have a feeding value of approximately 80% of PRG (Keating and O' Kiely, 2000) and was included as €80 per tonne DM in the recent study.

5.2.3. Statistical analysis

This study combined data from two studies that were conducted contemporaneously and adjacent to each other at the same site and the methods of measurement used (including harvest dates etc.) were common to both studies. The plots selected were from the study described by O'Donovan *et al*., (2021) in Chapter 3 included the control treatment and the plots that received post-emergence herbicide treatments in spring 2010. These latter plots received high rates of fertilizer K throughout the study. Likewise, the plots selected from the study described in Chapter 4 received high rates of fertilizer K throughout the study and docks m^{-2} and grass and dock herbage DM production were not affected by the fertilizer K treatments in the latter study. Post-emergence herbicides were applied to some of these plots, which along with the natural variation in dock numbers in plots across the site set up these 80 plots with a wide range of docks m^{-2} across plots in autumn 2010. This variation was used to investigate the impact of dock numbers in autumn on the economics of herbage production from each of these plots in subsequent years, in particular between 2012 and 2016.

The relationships between dock numbers per plot at each assessment date and (i) dock numbers per plot at subsequent assessment dates, (ii) annual dock herbage production DM per plot, (iii) annual grass herbage DM production per plot, (iv) annual total herbage DM per plot, (v) PRG herbage DM production per plot in 2016 and (vi) NSG herbage DM production in 2016 were examined using liner regression to calculate correlation coefficients (r).

Likewise, the relationships between annual dock herbage DM production per plot and (i) annual grass herbage DM production per plot and (ii) annual dock herbage DM production per plot were examined using liner regression to calculate correlation coefficients (r). Also, the relationship between annual grass herbage per plot and annual total herbage per plot were examined using liner regression to calculate correlation coefficients (r).

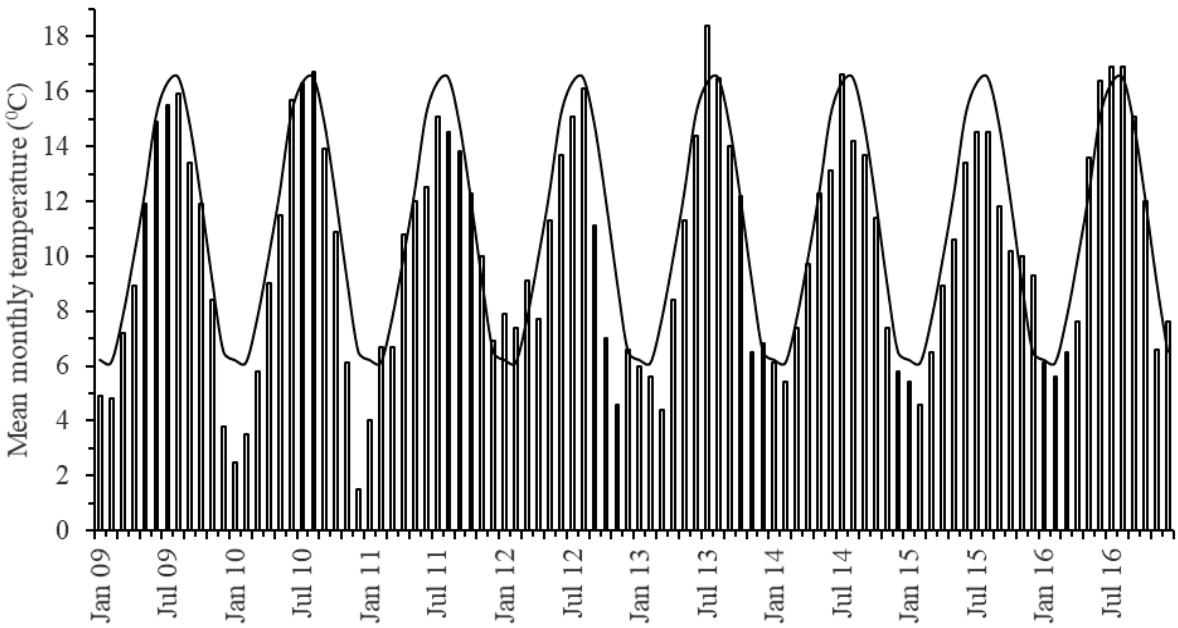
Finally, correlation coefficients (r) were also calculated for the relationships between annual NSG herbage DM production in 2016 and (i) annual PRG herbage DM production in 2016, (ii) annual dock herbage DM production in 2016 and (iii) annual total herbage DM production in 2016 using liner regression. The software package MSTAT was used for statistical analysis.

5.3. Results

5.3.1. Meteorological data

Meteorological data was obtained from a Met Eireann (www.met.ie) weather station approx. 800 m from the experimental site. The mean annual air temperature was lower in each of the seven years of this study than the previous ten-year average (11°C). The winters of 2009/2010 and 2010/2011 were exceptionally cold (Figure 5.1). The annual rainfall amounts each year were similar to the ten-year average (1073 mm). The rainfall during November 2009 was twice normal and there was exceptionally high rainfall during the months of June and August 2012 and in December 2015. Rainfall in December 2015 was almost five times the 10-year average rainfall for December.

(a)



(b)

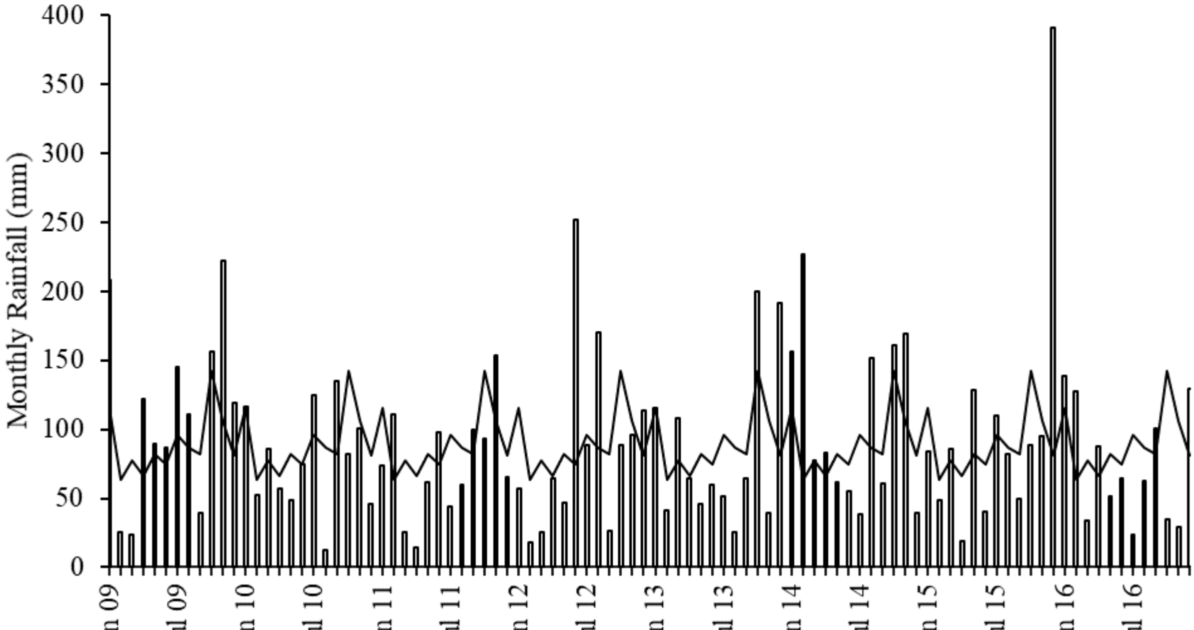


Figure 5.1 Monthly air temperature (a) and monthly rainfall (b) at the experimental site between 2009 and 2016. The columns show the levels during the experiment and the lines show the lines show the averages of the previous 10 years

5.3.2. Dock Numbers

There was a mean of approximately 3.3 docks m^{-2} across the 80 plots between the autumn 2010 and spring 2013 (Figure 5.2). Dock numbers increased to 6.1 m^{-2} in autumn 2013, 7.5 in spring 2014 and 8.4 in autumn 2014. Numbers dipped over the winter to 7.9 in spring 2015 and increased again to 11.5 docks m^{-2} in autumn 2015 (Figure 5.2).

Throughout the experiment there were strong correlation coefficients (>0.75; P<0.001) between dock numbers at each assessment date and subsequent dock numbers (Table 5.1). These correlations tended to become stronger over time during this study.

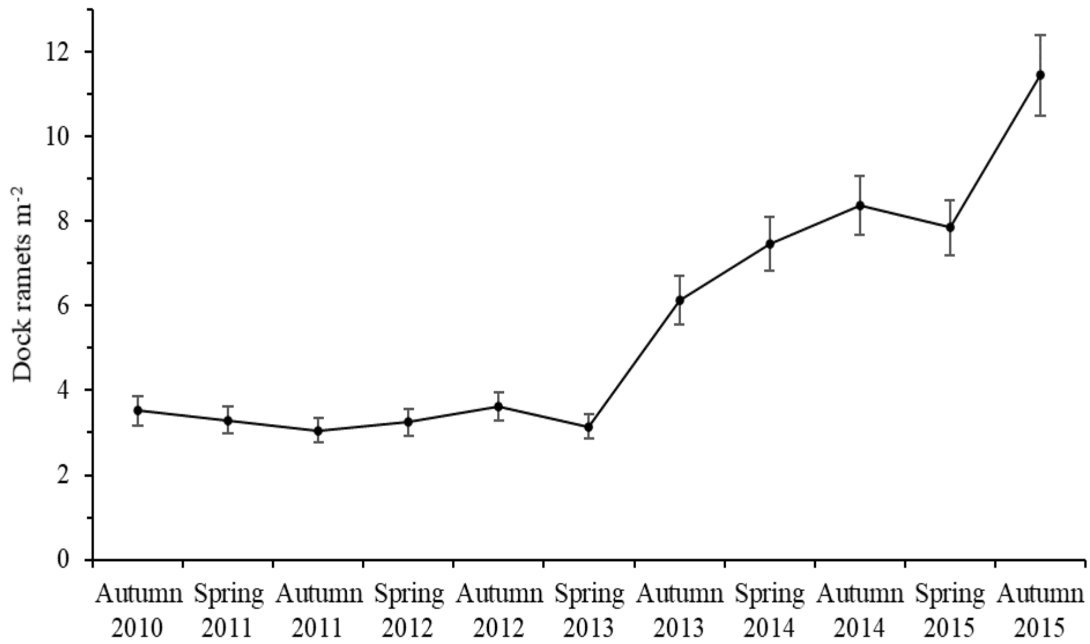


Figure 5.2 Mean number of dock ramets m^{-2} ± standard error for each mean (S.E.) between autumn 2010 and autumn 2015. Error bars = S.E.

Table 5.1 Correlation coefficients (r) between dock numbers m^{-2} at different stages of the study (n = 80)

Dock Numbers	Spring 2012	Autumn 2012	Spring 2013	Autumn 2013	Spring 2014	Autumn 2014	Spring 2015	Autumn 2015
Autumn 2010	0.817***	0.835***	0.813***	0.810***	0.815***	0.822***	0.752***	0.795***
Spring 2011	0.946***	0.959***	0.925***	0.931***	0.922***	0.838***	0.893***	0.919***
Autumn 2011	0.965***	0.984***	0.946***	0.950***	0.960***	0.964***	0.918***	0.933***
Spring 2012		0.958***	0.915***	0.922***	0.934***	0.958***	0.923***	0.910***
Autumn 2012			0.932***	0.941***	0.956***	0.963***	0.923***	0.932***
Spring 2013				0.971***	0.946***	0.959***	0.939***	0.951***
Autumn 2013					0.952***	0.966***	0.936***	0.962***
Spring 2014						0.962***	0.938***	0.938***
Autumn 2014							0.952***	0.956***
Spring 2015								0.952***

***P<0.001

5.3.3. Dock numbers and dock and grass herbage harvested for silage

Total grass and dock herbage DM harvested for silage (t ha^{-1}) was 7.8 in 2012, 9.9 in 2013, 11.6 in 2014, 10.0 in 2015, 11.0 in 2016 (Figure 5.3). As a proportion of total herbage DM harvested for silage dock herbage DM was 0.04 in 2012, 0.13 in 2013, 0.25 in 2014, 0.30 in 2015 and 0.31 in 2016 (Figure 5.3).

There were positive correlation coefficients between dock numbers and subsequent dock herbage DM harvested for silage throughout the study (Table 5.2). There was a tendency for correlation coefficients to strengthen over time during the study and especially from 2013 onwards when correlation coefficients were generally >0.79; P<0.001. There were also strong positive correlation coefficients between dock numbers and the total quantity of dock herbage DM harvested for silage combined over the years between 2012 and 2016.

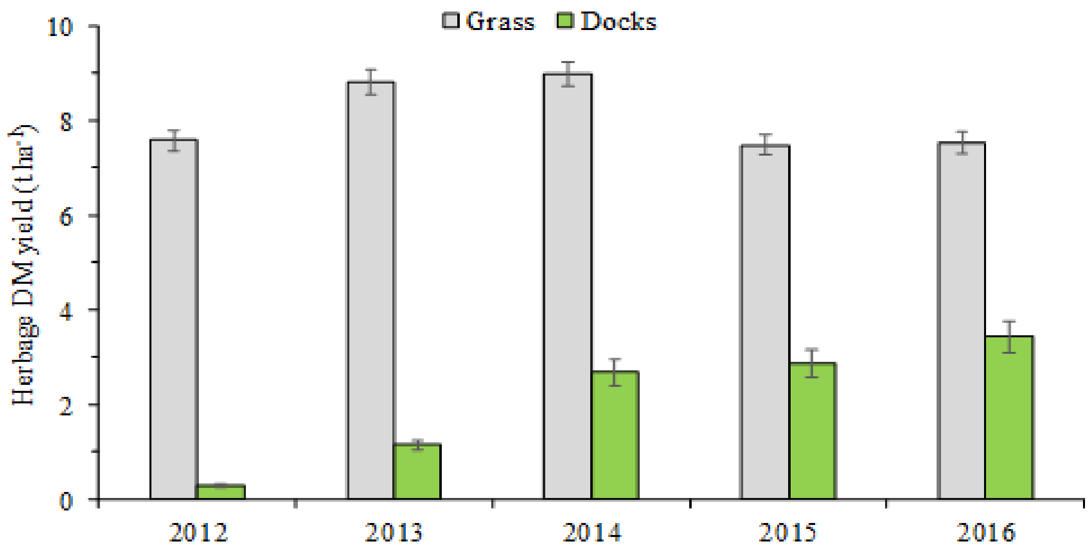


Figure 5.3 Grass and dock herbage yields (harvested for silage) ± standard error for each mean (S.E.) for each year between 2012 and 2016. Error bars = S.E.

In contract to dock herbage DM harvested for silage there was no relationship between grass herbage DM harvested for silage in 2012 and dock numbers in 2010, 2011 and 2012 (Table 5.2). Furthermore, from 2013 onwards, there were inverse correlation coefficients between docks numbers m^{-2} and subsequent grass herbage DM harvested for silage. There was also a tendency for these inverse correlation coefficients to get stronger over time during the study. There were also strong inverse correlation coefficients between dock numbers and the total quantity of grass herbage DM harvested for silage between 2012 and 2016 (Table 5.2).

Table 5.2 Correlation coefficients (r) between annual dock numbers m^{-2} and grass and dock herbage DM (harvested for silage) for each year between 2012 and 2016, and combined for all years

Year:	2012	2013	2014	2015	2016	All years
Dock Numbers			Dock herbage (t ha^{-1})			
Autumn 2010	0.510***	0.757***	0.772***	0.788***	0.674***	0.796***
Spring 2011	0.570***	0.794***	0.829***	0.857***	0.756***	0.866***
Autumn 2011	0.626***	0.794***	0.853***	0.888***	0.801***	0.898***
Spring 2012	0.668***	0.723***	0.788***	0.830***	0.774***	0.845***
Autumn 2012	0.607***	0.788***	0.858***	0.882***	0.815***	0.900***
Spring 2013		0.820***	0.870***	0.887***	0.802***	0.907***
Autumn 2013		0.814***	0.852***	0.878***	0.799***	0.897***
Spring 2014			0.859***	0.879***	0.821***	0.902***
Autumn 2014			0.863***	0.891***	0.850***	0.919***
Spring 2015				0.854***	0.811***	0.880***
Autumn 2015				0.872***	0.806***	0.895***
Dock Numbers			Grass herbage (t ha^{-1})			
Autumn 2010	NS	-0.599***	-0.732***	-0.743***	-0.594***	-0.722***
Spring 2011	NS	-0655***	-0.806***	-0.828***	-0.675***	-0.805***
Autumn 2011	NS	-0.682***	-0.849***	-0.875***	-0.734***	-0.857***.
Spring 2012	NS	-0.625***	-0.796***	-0.825***	-0.717***	-0.807***
Autumn 2012	NS	-0.689***	-0.850***	-0.868***	-0.739***	-0.859***
Spring 2013		-0.653***	-0.846***	-0.856***	-0.709***	-0.841***
Autumn 2013		-0.639***	-0.851***	-0.857***	-0.701***	-0.834***
Spring 2014			-0.870***	-0.866***	-0.726***	-0.860***
Autumn 2014			-0.858***	-0.878***	-0.765***	-0.871***
Spring 2015				-0.833***	-0.711***	-0.822***
Autumn 2015				-0.838***	-0.712***	-0.837***

***P<0.001; [NS] Not significant

There was no significant correlation between dock herbage DM harvested for silage and grass herbage DM harvested for silage in 2012 (Table 5.3). However, in each of the subsequent years (2013 to 2016) there were strong inverse correlation coefficients between dock herbage DM production and grass herbage DM production (Table 5.3). Furthermore, when herbage DM harvested for silage was summed for each year between 2012 and 2016 there was a strong inverse correlation between dock and grass herbage production (Table 5.3).

Grass herbage DM harvested for silage was positively correlated with total herbage DM harvested for silage in each during the study (Table 5.3). The correlation coefficient in 2012 was stronger than in any of the subsequent years. Likewise, there was a positive correlation between the sum of all grass DM harvested for silage and total herbage DM harvested for silage between 2012 and 2016.

In contrast, there were no significant correlations between dock herbage DM harvested for silage and total DM harvested for silage in 2012, 2013 and 2016 (Table 5.3). In 2014 and 2015 there were weak inverse correlations between dock herbage DM harvested for silage and total DM harvested for silage. Summed for all years between 2012 and 2016 there was a weak inverse correlation coefficient between dock herbage DM harvested for silage and total herbage DM harvested for silage (Table 5.3).

In terms of the NSG component of herbage DM harvested from plots in 2016, there was an inverse correlation between NSG and perennial ryegrass herbage DM production (Table 5.5). In contrast there were positive correlations between NSG herbage DM in 2016 and (i) dock herbage DM in 2016 and (ii) docks m^{-2} in 2015 (Table 5.5). Furthermore, NSG made a positive contribution to total herbage DM production in 2016 (Table 5.5).

Table 5.3 Correlation coefficients (r) between dock herbage DM, grass herbage DM and total herbage DM (n = 80) harvested for silage in each year between 2012 and 2016, and combined for all years

	2012	2013	2014	2015	2016	All years
Grass herbage (t ha^{-1})			Dock herbage (tha^{-1})			
2012	NS					
2013		-0.776***				
2014			-0.936***			
2015				-0.947***		
2016					-0.853***	
All years						-0.938***
Total herbage (t ha^{-1})			Dock herbage (tha^{-1})			
2012	NS					
2013		NS				
2014			-0.378***			
2015				-0.306**		
2016					NS	
All years						-0.262*
Total herbage (t ha^{-1})			Grass herbage (t ha^{-1})			
2012	0.913***					
2013		0.538***				
2014			0.679***			
2015				0.597***		
2016					0.533***	
All years						0.579***

*P<0.05; **P,0.01; ***P<0.001; ^{NS} Not significant

Table 5.4 Correlation coefficients (r) between dock numbers throughout the study and the economic value of herbage harvested for silage between 2012 and 2015 as outlined in Figure 5.3

	2012	2013	2014	2015	2016	All years
Autumn 2010	NS	-0.271*	-0.609***	-0.607***	-0.442***	-0.565***
Spring 2011	NS	-0.325**	-0.691***	-0.699***	-0.519***	-0.655***
Autumn 2011	NS	-0.365***	-0.747***	-0.758***	-0.577***	-0.721***
Spring 2012	NS	-0.338**	-0.712***	-0.722***	-0.572***	-0.682***
Autumn 2012	NS	-0.381***	-0.745***	-0.752***	-0.574***	-0.723***
Spring 2013		-0.300**	-0.725***	-0.723***	-0.533***	-0.681***
Autumn 2013		-0.285**	-0.752***	-0.733***	-0.527***	-0.680***
Spring 2014			-0.780***	-0.750***	-0.545***	-0.722***
Autumn 2014			-0.754***	-0.761***	-0.582***	-0.725***
Spring 2015				-0.711***	-0.537***	-0.676***
Autumn 2015				-0.703***	0.548***	-0.690***

*P<0.05; **P,0.01; ***P<0.001; [NS] Not significant

Table 5.5 Correlation coefficients (r) between weed grass herbage yield in 2016 and yields of perennial ryegrass (PRG), dock and total herbage in 2016, all as harvested for silage

	Weed grass herbage ($t\ ha^{-1}$)
PRG herbage ($t\ ha^{-1}$)	-0.506***
Dock herbage ($t\ ha^{-1}$)	0.301**
Total herbage ($t\ ha^{-1}$)	0.426***
Docks m^{-2} in 2015	0.486***

**P,0.01; ***P<0.001

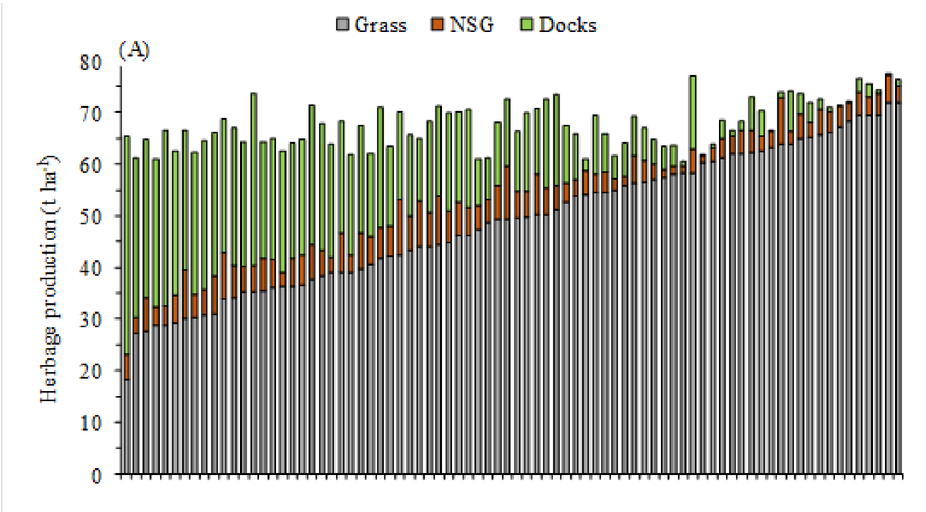


Figure 5.4 (A) The estimated cumulative yield of herbage (grass; predominantly perennial ryegrass + NSG herbage; predominantly Agrostis spp. + dock herbage) produced over five years (2012-2016). Each bar represents an individual plot (n=80).

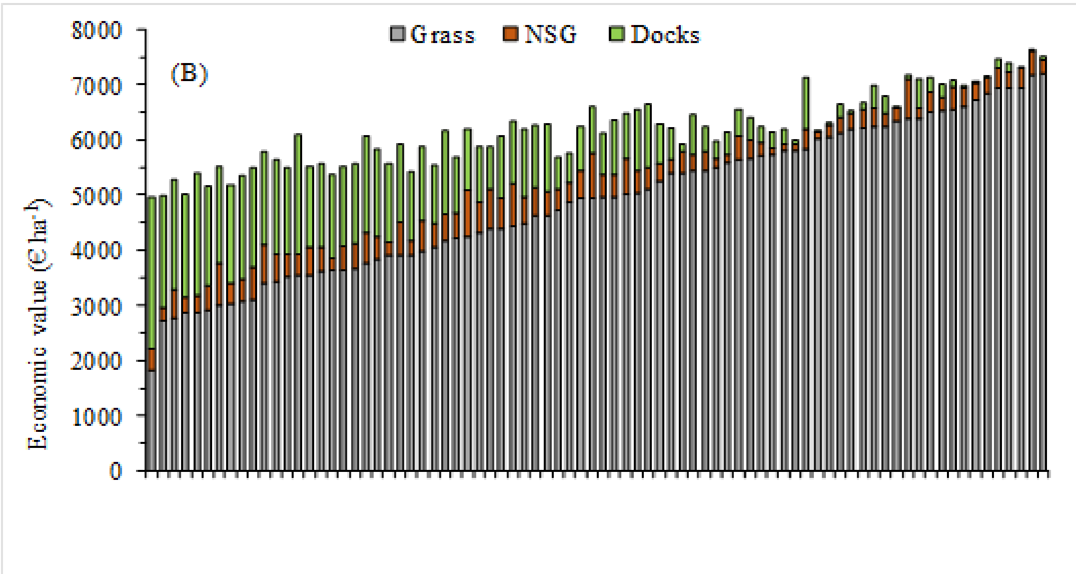


Figure 5.4 (B) The estimated economic value of the herbage harvested with grass herbage (predominantly perennial ryegrass) valued at €100 per t DM, NSG herbage (predominantly Agrostis spp.) at €80 per t DM and dock herbage at €65 per t DM. Each bar represents an individual plot (n=80).

5.3.4. Economic value of estimated herbage DM production

Total estimated annual herbage DM production between 2012 and 2016 from each plot averaged 67.7 t ha^{-1} (SE = 0.50) or an average of 13.54 t ha^{-1} per year. Summed for the five years perennial ryegrass herbage DM (t ha^{-1} mean ± SE) was 48.9 ± 1.47, NSG herbage DM was 4.9 ± 0.23 and dock herbage DM was 13.9 ± 1.18 (Figure 5.4A). In terms of the economic value of this herbage, the total value (mean ± SE) was €6187 ± 73.2, made up of perennial ryegrass €4889 ± 146.9, NSG €396 ± 18.3 and docks €903 ± 76.7 (Figure 5.4B).

There was no significant relationship between the economic value of herbage produced in 2012 and docks m^{-2} in 2010, 2011 or 2012 (Table 5.4). There were weak inverse correlation coefficients between docks m^{-2} in 2013 and the economic value of herbage produced in 2013. There were stronger inverse correlation coefficients ($r > 0.75$; $P < 0.001$) between docks m^{-2} in 2014 and the economic value of herbage produced in 2014 (Table 5.4). Correlation coefficients tended to be weaker in 2015 and weaker again in 2016 compared with 2014 (Table 5.4). The sum of the economic value of herbage DM produced between 2012 and 2016 was inversely correlated with docks m^{-2} throughout the study (Table 5.4 and figure 5.5A). There was an inverse correlation ($P<0.001$) between the economic value of annual herbage DM production between 2012 and 2016 and docks m^{-2} in each plot in autumn 2010 (Table 5.4). Likewise, there was an inverse correlation ($P<0.001$) between the economic value of annual herbage DM production between 2014 and 2015 and docks m^{-2} in each plot in autumn 2010 (Table 5.4 and figure 5.5B).

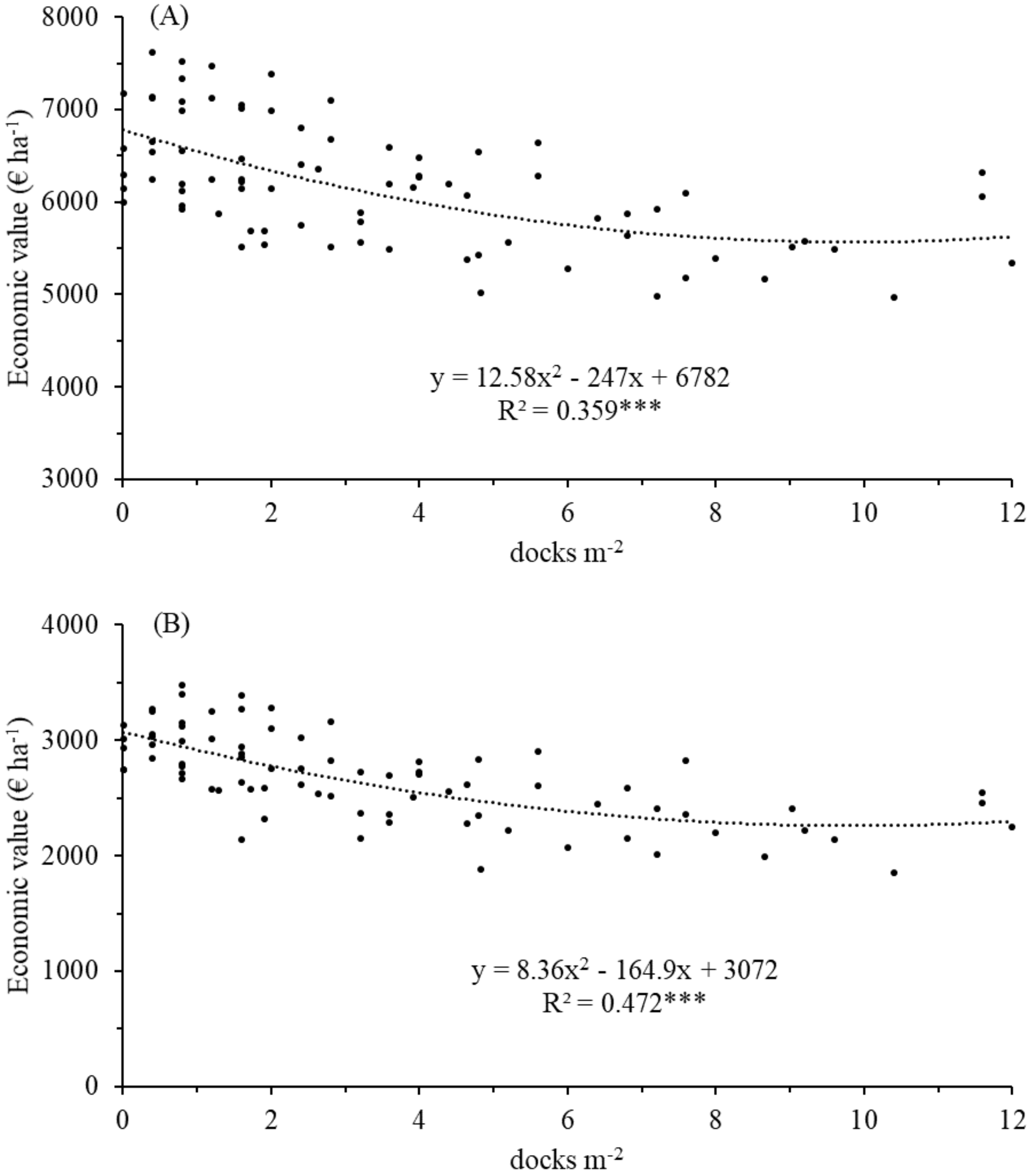


Figure 5.5 (A) The relationships between dock numbers in autumn 2010 and the economic value of estimated herbage produced between 2012 and 2016 and (B) the relationships between dock numbers in autumn 2010 and the economic value of estimated herbage produced in 2014 and 2015

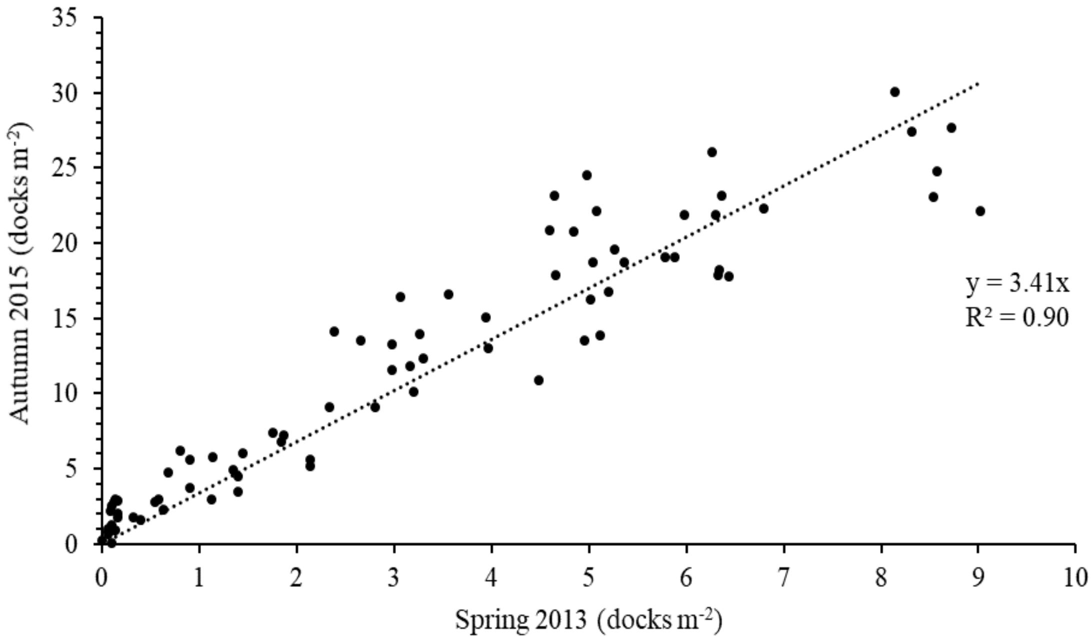


Figure 5.6 The relationship between docks m^{-2} in spring 2013 and autumn 2015

5.4. Discussion

The plots as described above were used in the present study to investigate the possibility of identifying a threshold dock population in newly established leys to determine the need for application of post-emergence herbicides. The answer to this question depends on the economic impact of the docks on herbage production in the years following the establishment of a new ley. In both studies only the herbage DM that was harvested for silage in two harvests per year, the first in late May and the second in late July, was measured. Using the economic value of herbage from these two harvests would underestimate the true economic impact on an annual basis and therefore annual herbage production for each plot was estimated as described above. Estimated annual herbage DM production over five years (2012 to 2016) averaged 13.54 t ha^{-1}, which is in line with many other studies. Investigating economic impact over a long timeframe (seven years in the present study), was advocated by Pywell *et al.* (2010) and Huwer *et al*. (2005).

5.4.1. Dock numbers and herbage production

Following initial establishment and the application of post-emergence herbicides there was an average of 3.3 docks m^{-2}, which remained relatively static between autumn 2010 and spring 2013 (Figure 5.2). Docks m^{-2} ranged between 0.1 and 9.9 across plots during this timeframe. This timeframe spanning the first 2 to 3 years after initial establishment of seedlings has been described as the juvenile phase of development (Pino *et al.*, 1995) during which that root reserves increase, and new shoots are developing. Hopkins and Johnson (2002) also reported relatively static docks m^{-2} in their study of juvenile docks (0-3 years old). Furthermore, in the latter study it was reported that docks contributed 0.9% of herbage DM and 4.6% of herbage DM in year 2 and year 3, respectively. These percentages are in line with the results of the present study where docks contributed 3.8% of herbage DM in 2012 or year 3 of the present study.

The juvenile phase was followed by a phase of clonal propagation during which timeframe there was a substantial increase in docks m^{-2}, increasing from an average of 3.3 in spring 2013 to 11.5 docks m^{-2}, ranging between 0.1 and 30.2, in autumn 2015 (Figure 5.2 and 5.6). During this phase, plots with higher numbers of docks m^{-2} in spring 2013 contributed to proportionally greater numbers in subsequent years because there were higher initial numbers to support clonal propagation. As indicated in Table 5.1 and Figure 5.6, 90% of the variation in dock m^{-2} in the autumn 2015 was explained by the variation in docks m^{-2} in spring 2013. During this timeframe the docks had the biggest impact on herbage production accounting for 12.6% of herbage DM in 2013 and increasing to 31.4% in 2016. Hopkins and Johnson (2003) reported a fivefold increase in dock ramet density over 4 years, which corresponds to the period of rapid increase in dock numbers in the present study. Furthermore, Courtney (1985) reported docks comprised up to 50% of the herbage DM, which is in line with plots at the higher end of the range, i.e., from <5% to 76% of total herbage DM in the present study in 2016.

In general, there was good agreement between dock numbers and dock herbage production in the present study particularly from 2013 onwards (Table 5.3). Likewise, there were inverse correlations between dock numbers and grass herbage DM production from 2013 onwards. Hongo (1989b) reported poor correlations between dock numbers and grass yields, which is somewhat in agreement with the present study because the study by Hongo (1989b) was concerned with juvenile docks (<3 years old). There was no significant correlation between docks m^{-2} and grass herbage DM production in 2012, when the docks were three years old in the present study (Table 5.2).

The impact of docks m^{-2} on grass herbage production was most clear-cut in 2014 and 2015 in the present study. The correlations between dock m^{-2} and grass herbage DM tended to be weaker for grass herbage DM production in 2016, although the most contemporaneous correlation was with docks m^{-2} in 2015 (Table 5.2) because, unfortunately, docks m^{-2} were not measured in 2016. Nevertheless, there is also evidence of a weakening relationship between dock herbage DM production and grass herbage DM production in 2016 relative to 2014 and 2015 presented in Table 5.3, where the correlation coefficient between dock herbage DM and grass herbage DM declines from -0.947 in 2015 to -0.853 in 2016. In contrast to the present study, Oswald and Haggar (1983) concluded that dock numbers were a poor indicator of the effects of docks on grass herbage DM production. The latter study examined mature docks (> 8 years old) that were older that the docks in the present study. It is possible that as docks get older (>8 years old) that they are less competitive in the sward, which was beyond the timeframe of the present study.

Towards the end of the present study, it was evident that there was an ingress of NSG into plots, particularly in 2016, that was not evident in the earlier years. This ingress was positively correlated with docks m^{-2} and dock herbage DM production and inversely correlated with PRG herbage DM production in 2016. This indicates that greater docks m^{-2} and dock herbage production per plot favoured the ingress of NSG at the expense of the PRG component of the sward. This is another consequence of dock infestation of grassland that is detrimental to the agronomic productivity of swards and that, as far as we are aware, has not been previously reported.

5.4.2. Herbage Production and competition between species

There were inverse relationships between dock herbage DM production and grass herbage DM production for each year between 2013 and 2016 and for the sum of herbage production between 2012 and 2016 (Table 5.3). Oswald and Haggar (1983) attributed the decline in grass growth due to competition from docks, mainly by shading and from root competition for moisture and nutrients. It is clear that PRG was the dominant component of the sward during the first three years (2010 to 2012) of the present study. However, from 2013 onwards it is also clear that the docks became increasingly competitive in the plots, particularly those with the highest initial populations in the early years of this study. Niggli *et al*. (1993) attributed increased competitiveness of the docks to increased dock numbers and to the increase in dock root reserves, which favoured more rapid regrowth after defoliation.

Docks and PRG both exhibit the phalanx form of clonal growth i.e., they expand slowly by closely connected ramets (Cheplick, 1997; Pino *et al*., 1995) and hence come into direct competition with each other for space within the sward. *Agrostis stolonifera*, on the other hand, exhibits the guerrilla form of clonal growth with more widely spaced ramets (Dong *et al*., 1995) that allow it to seek out more favourable locations such as open (less competitive) spaces within the sward (Xue-Hua *et al*., 2006). Ground cover by the dock canopy tends to increase during the summer and decline during the winter. It is possible that the NSG were able to take of advantage of these changes in ground cover better than PRG, which would explain the increasing ingress of NSG as a consequence of the docks becoming more competitive in the sward. Greater ingress of NSG could also partly explain the declining correlation coefficients between grass herbage DM production and dock herbage DM production in 2016 relative to 2015: The NSG were better able to resist competition from the docks than the PRG and, hence maintain relatively higher grass DM production. Dock herbage production was inversely related to total herbage DM production in 2014 and 2015 but not in 2016 (Table 5.3).

5.4.3. A threshold dock population density for the application of post-emergence herbicide, using estimated annual herbage yields

Determining such a threshold depends on the negative economic impact of the docks on overall herbage production including docks, PRG and NSG. The cost of a single application of post-emergence herbicide is approximately €130 ha^{-1} comprised of €100 ha^{-1} for the herbicide and €30 ha^{-1} for the cost of application. In Figure 5.5A the intercept value of estimated herbage produced over five years (2012-2016) was €6782 ha^{-1}; i.e. mainly PRG with very little dock or NSG. Taking into account the cost of herbicide application and using the equation in Figure 5.5A, the breakeven number of docks in 2010 was 0.6 m^{-2}. However, there is considerable uncertainty around this number with greater than intercept economic values recorded dock numbers in 2010 ranging between 0 and 2.8 m^{-2} in 2010 (Figure 5.5A). The mean number of docks in 2010 in the plots (n = 15) with greater than intercept economic values was 1.12 m^{-2} and the median was 0.8 m^{-2}. To achieve >95% of the intercept economic value for herbage production between 2012 and 2016 there needed to be <1.5 docks m^{-2} in 2010. Conducting a similar evaluation with herbage production confined to 2014 and 2015 gave a similar set of results to above. Based on the equation in Figure 5.5B the breakeven acceptable number of docks in 2010 was 0.8 m^{-2}. There was similar uncertainty to above with greater than intercept economic values recorded with docks ranging between 0 and 2.8 m^{-2} in 2010 (Figure 5.5B). Likewise, the mean number of docks in 2010 in the plots (n = 13) with economic values greater than the intercept value was 1.17 m^{-2} and the median was 0.8 m^{-2}. To achieve >95% of the intercept economic value for herbage production in 2014 and 2015 there needed to be <1.0 docks m^{-2} in 2010. Hence, a rough 'rule of thumb' threshold number of docks in the year of establishment of a grass sward is between 1.0 and 1.5 m^{-2}.

While €100 per t DM is a reasonable value of perennial ryegrass harvested for silage during the main growing season, this value underestimates the value of grazed pasture in the spring and autumn. Scarce pasture for grazing in the spring and autumn can be valued relative to the cost of alternatives; grass silage (€130 per t DM) and concentrates (€270 per t DM) according to Finneran *et al*. (2012) and Hanrahan *et al*. (2018). The nutritive value of these feeds relative to grazed pasture has to be taken into account along with the costs associated with feeding these feeds relative to grazed grass. For example, silage has typically lower nutritive value than grazed pasture in spring and is typically fed to cattle indoors; the silage has to be presented to the cattle at the feed barrier and there is the associated costs of managing the slurry produced. Nevertheless, it is unlikely that these considerations greatly change the estimated threshold numbers of dock m^{-2} in the year of grassland establishment.

5.4.4. Implications

In farming practice there can often be a no clear association made between a few apparently innocuous dock seedlings m^{-2} in a new ley and the economic damage that they can subsequently cause to herbage production. The present study enables the projection of future economic losses that should help grassland managers plan dock control strategies, which could entail the timely and eco-efficient application of a post-emergence herbicide or the adoption of alternative measures. Such strategies could include the adoption of a stale seedbed technique promoting the emergence of dock seedlings that are subsequently eliminated by cultivations immediately prior to concomitant to sowing the grass seed as outlined by Ringselle *et al.* (2019). Furthermore, Keary and Hatcher (2004) and Humphreys (1995) showed that the number of emerging dock seedlings can be supressed by practices that promote the rapid and dense establishment of PRG and white clover. Such practices include sowing seeds close to the soil surface during weather conditions favourable to rapid establishment of the sward canopy along with a higher seeding rate of the sown species.

5.5. Conclusions

The present study was conducted over a longer timeframe than many similar studies. It involved a wide range of population densities of established docks in grassland plots that were approximately one year old and homogenous in age at the commencement of this study. Docks m^{-2} did not change during the following two years. Between the fourth year (2013) and the seventh year (2015) there was a 3.4-fold increase in dock numbers due to clonal propagation of existing docks in each plot. During the latter timeframe the contribution of dock herbage DM to total herbage DM production each year increased from an average of 12.6% in 2013 to 31.4% in 2016. It was also during this timeframe that docks were most detrimental to grass herbage DM production and to the economic value of the herbage produced, particularly during 2014 and 2015. Higher dock population densities favoured the ingress of NSG into plots during the later years of this study, which was further detrimental to the economic value of the herbage produced. Most eco efficient control of docks using post-emergence herbicides can be achieved during the seedling stage. A seedling population density of as low as 0.6 docks m^{-2} can justify the cost of post-emergence herbicide from a solely economic perspective although there is considerable uncertainty around this number. Where post-emergence herbicides are not applied, every effort should be made to limit dock seedling numbers to no more than 1.0 m^{-2} in newly established leys.

Chapter 6. Discussion and Conclusions

This thesis set out to improve the control of docks in intensively managed grassland using IPM techniques. This topic was chosen due to its importance to Ireland's national economy (O' Donovan *et al*., 2010) and because farmers continue to report unsatisfactory control of docks (Creighton *et al*., 2010). This problem represents a classical dichotomy between scientific knowledge and outcomes at farm level. Docks are a well-studied weed species (Zaller, 2004) with a wide range of control options (Anon, 2019; Van Evert, 2020). The scientific literature on dock biology, despite being somewhat dated, is extensive and comprehensive (Foster, 1989; Zaller, 2004; Bond *et al*., 2007). However, the bulk of the literature on dock control options in recent years has shifted its focus from chemical control options to non-chemical options, which is following the EU policy direction towards reduced pesticide inputs (Anon, 2012). Also, there is a lack of on-farm or near-farm research looking at non-herbicide dock control options, especially over a longer timescale.

Therefore, this thesis focussed on these knowledge gaps and set up experiments to test three hypothesis:

1. Can we improve the eco-efficiency of dock herbicide use in conventionally managed intensive grassland?
2. Can we influence dock population density and/or dock biomass production by exploiting the dock's poor competitiveness for potassium with grass at low plant-available soil potassium concentrations?
3. Can we reliably predict forward the population dynamics of docks and their effects on grass herbage DM production based on the population density of established seedlings?

Before drawing conclusions from the thesis, it is worthwhile to note several unique aspects of the experimental design that improved its scientific merit and relevance to grassland farmers and agronomists:

Homogenous and naturally occurring dock population

In Chapters 3 and 4, it was recorded that most of the docks in both studies germinated shortly after reseeding in 2009 and were thus homogenous in age as the experiments progressed. This homogenously aged dock population allows conclusions to be drawn that are very applicable to farmers and agronomists and allows more precise identification of knowledge gaps for further study. Groenendael (1998) pointed out that weed distribution is heterogenous in nature and requires careful consideration of the experimental technique to overcome this problem. Oswald and Haggar (1983), Courtney (1985) and Hopkins and Johnson (2002) used dock transplants or carefully selected dock populations growing in situ to achieve homogenous dock populations. The methodology in Chapters 3 and 4 is an alternative approach. The obvious drawback with the methodology in the present thesis is the requirement to have large plots and sufficient replications to overcome the spatial variation of dock occurrence.

Duration of experiments

The main conclusions in Chapters 4 and 5 did not become apparent until towards the end of the experimental period. Specifically, the findings that the relationship between STK and dock root DM and dock herbage DM production (Chapter 4) and the effects of the inter-species competition between dock, PRG and NSG (Chapter 5) did not become apparent until 2016. In the case of STK, it is well known that certain soils have a high K buffering capacity, which was the case at the present experimental site (section 4.4.1) and the STK in such soils required a longer timeframe to align with the experimental treatments. Results from studies encompassing a longer timeframe also align with farm practice as STK is measured every five years and resulting fertiliser applications do not vary much from year to year. Experiments on integrated weed management by Huwer *et al*. (2005) and Pywell *et al*. (2010) concluded that the duration of experiments is critical for unveiling complex relationships in perennial weed species, thus justifying the duration of the present study.

Experimental site

The experimental site was located as part of a field on a conventional dairy farm with typical management practices such as grazing intensity, silage cutting and nutrient management (except K fertiliser and land spreading of organic manures in the area dedicated to Chapter 4). Two germane points to note: firstly, there was no special management to enhance grass sward density on the site and secondly, the site received high inputs of artificial fertilizers and was cut for silage twice per year for seven years (practices found to be associated with higher incidence of docks; Haggar,1980; Peel and Hopkins, 1980 and Humphreys *et al*., 1997). The site management is very pertinent when considering the longevity of apparent dock control from the SSH treatments in Chapter 3, the lack of dock seedling recruitment (once the grass canopy had closed in) in Chapters 3 and 4 and lastly, the increases in docks m^{-2} and dock herbage DM production in Chapters 3 and 4.

Based on this, it can be concluded that an established grass sward largely prevents the recruitment of dock via seedlings but promotes recruitment of docks via clonal propagation and promotes dock herbage DM production.

Clonal Propagation

Until Pino *et al.* (1995), many authors believed the recruitment of new docks in grassland was primarily from seed either through opportunistic establishment in vegetation gaps (gaps in the grass sward) or where the competing vegetation was supressed (Section 2.5.2). Pino *et al*. (2005) demonstrated that docks were a true clonal species and postulated that that clonal propagation is important for their survival and spread in closed communities (e.g., established grassland). In terms of life history, Harper (1977) argued that seeds and seedling stages are of less importance for the propagation of plants exhibiting clonal growth than annual plants. Recruitment from seed is relatively rare for clonal plants and is mostly associated with newly disturbed sites, such as ground cultivated for the sowing of a new ley. The results of Chapter 3 are the first published evidence that tie together many strands of previous research. Firstly, it was shown how dock populations arise from seedling recruitment after widescale soil disturbance events (e.g., sowing of the new ley). Secondly, once the grass sward is established (a closed community), dock seedling recruitment is virtually non-existent. Thirdly, dock population density increases linearly due to clonal propagation between the fourth and sixth years after the initial recruitment event (Table 6.1).

Table 6.1. Changes of dock population densities throughout the experiments described in Chapters 3, 4 and 5

Year Autumn to autumn	Year No.	Dock population density
2009	0	Germination and establishment
2010	1	Declining number of seedlings
2011	2	Stable numbers of docks
2012	3	
2013	4	Increasing number of clones
2014	5	
2015	6	
2016	7	Not measured

Hence, in year 1 (between sowing in 2009 and autumn 2010) there was a transition between newly establishing seedlings, seedling mortality and relatively stable average dock population density by the end of year 1. Between autumn 2010 and spring 2013 there was no change in average dock population density, i.e., during years 2 and 3 and the beginning of year 4. Between spring 2013 and autumn 2015 there was more-or-less a continuous increase in average dock population density due to clonal propagation, i.e. between years 4 and 6. In year 4 there was a transition between stable average dock population density and a 3.4-fold increase in average dock population density between years 4 and 6 (Table 6.1.). It is also important to bear in mind that in constructing this table that the NLH and EGH treatments were excluded.

Fourth, once docks are sufficient in size and population density (to comprise 10% to 20% of the total sward DM production), docks exert their dominance in the ecosystem and can affect species change (Chapter 5). Lastly, it is important to note that the results from Chapter 5 suggests that the once the initial seedling population has stabilised and established a tap root, this has a strong legacy effect on dock populations especially because of clonal propagation. This stands to reason as clonal growth in phalanx species (like docks) is slow with tightly spaced ramets that originate from the initial seedling as in the case of docks.

6.1. Improving the effectiveness of dock herbicides in conventionally managed intensive grassland?

As discussed in Chapter 2, there is almost no recent (within 20 years) scientific literature examining the herbicide control of docks. This is extraordinary considering that 100% of pesticides applied onto Irish grassland are herbicides (Anon, 2019) and over 50% are for dock control (pers. comm.: Maughan, C). There are even fewer references to seedling dock herbicide control in the literature (except Blair and Holroyd, 1973) even though it is commonly inferred that dock seedlings are easily killed by herbicides. Also, the word ‘control’ on a herbicide label may not be fully understood and thus creates its own disappointments when farmers expectations are not met (Section 2.9.3.1).

What is well understood and studied is the poor ability of seedling docks to gain a foothold in established grassland. This is a combination of:

1. the grass sward interrupting the dock seed phytochrome system and preventing the dock seed from germinating (Chapter 2, section 2.6.2)
2. the grass sward (through shading) preventing large temperature fluctuations, especially rapid increases in temperature (Chapter 2, section 2.6.2)
3. the grass sward competing with the dock seedling for resources, thus preventing establishment (Chapter 2, section 2.6.3)

It is obvious that this ‘establishment weakness’ in dock biology could be hugely beneficial to farmers if a control mechanism is applied to manage the initial flush of dock seedlings after reseeding. Chapter 3 dealt with herbicides as a means of control, but this work is equally applicable to non-herbicide control options, especially management practices that enhance the seedling grass development or additional species that will increase the overall competition with the seedling docks.

The results of Chapter 3 were very clear:

Firstly, herbicides applied to seedling docks (NLH) reduced docks m^{-2} by up to 90% and increased total grass yield by up to 20% (4.8 t DM ha^{-1}) compared to the untreated control between 2012 and 2014. The most benefit occurred in 2014 when the dock proportion of the total sward herbage DM was 31% in the untreated control plots but only 1.4% in the Doxstar (NLH) plots. In comparison, herbicides applied to mature docks (EGH) reduced docks m^{-2} by up to 50% and increased total grass yield by up to 11% (2.7 t DM ha^{-1}) compared to the untreated control. EGH treatments that had the least effect on docks m^{-2} and herbage DM production also showed the most re-growth from dock roots and the lowest decrease in root biomass (Tables 3.3 and 3.4; Chapter

3). Another consequence of dock infestation is the replacement of PRG with NSG as shown in Chapter 5 and is a further reason to apply herbicides as early as possible in the dock's lifecycle. The EGH applications in Chapter 3 were applied when the docks were between two and three years old, and the docks had only minimal impact on grass herbage production. The results from Chapter 5 indicate that if EGH applications were delayed until the docks were five or more years old, as often happens at farm level, then the PRG component would have been somewhat replaced with NSG of lower feeding value, thus reducing the benefit of EGH applications. Savory and Soper (1973) also concluded that the long-term success of the herbicide treatments was dependant on the management of the sward (post-herbicide application) and the ability of the grasses to exploit the spaces left vacant by the removal of the docks.

Secondly, a well-managed grass sward is extremely efficient at preventing dock seeds/seedlings from germinating and/or establishing. This was very apparent in Doxstar (NLH) where docks m^{-2} remained static from Spring 2011 until the end of the experiment, indicating that little or no seedling recruitment occurred. What is unclear and worthy of further investigation is whether the grass sward primarily affected dock seed germination or dock seedling establishment. Ringsell *et al*. (2019) and Humphreys (1995) showed how a companion crop (spring barley and white clover, respectively) added to the grass sward seed mixture at sowing time, significantly reduced dock seed germination. Further work in this area should include higher grass seed rates, enhanced grass seed vigour from seed treatments, addition of various companion crops such as short-lived forbs like lucerne all with the aim of reducing dock seedling establishment. What is critical is that every effort should be made to reduce the initial dock seed germination during reseeding.

If pesticides are restricted in future (Anon, 2020), information will be required as to the best timing and rate of pesticide that is most effective at reducing docks m^{-2}. In Chapter 3, Doxstar-NLH (applied at 1.5 l/ha or half the full rate) gave a 91% reduction in docks $m^{-2,}$ whereas Doxstar-EGH (applied at 3.0 l/ha or the full rate) only gave 32% reduction in dock m^{-2}. Simply put, applying Doxstar onto seedling docks was six times more effective (per unit or litre) than applying Doxstar onto mature docks and, on average, NLH were twice as effective at reducing docks m^{-2} than EGH, irrespective of herbicide application rate.

What were the economic benefits of applying a herbicide? If we assume the value of a tonne of grass DM is €100 t DM^{-1} and a tonne of dock DM is €65 (Chapter 5), then the value of the herbage DM production is valued in Table 6.2.

Table 6.2 Economics of dock control based on data from Chapter 3. Herbage was valued on the basis of herbage DM production between 2012 and 2014 with PRG herbage DM valued at €100 t and dock herbage DM at €60 t

Treatment	Untreated control	Doxstar-EGH	Doxstar-NLH
Dock herbage DM			
(t ha^{-1})	5.2	1.97	0.23
(€ ha^{-1})	338	128	15
Grass herbage DM			
(t ha^{-1})	24.1	26.8	28.9
(€ ha^{-1})	2408	2678	2980
Total herbage DM			
(€ ha^{-1})	2746	2806	2994
Benefit over untreated control (€ ha^{-1})	0	60	248

Assuming a spray cost of €130/ha (€100 ha^{-1} herbicide cost and €30 ha^{-1} application cost; Chapter 5), it was not economically beneficial to control the docks in this experiment using Doxstar-EGH whereas it was very worthwhile using Doxstar-NLH. One has also to consider added benefits from the herbicides such as less dock seeds being added to the soil.

The monetary value placed on dock foliage is contentious and rarely considered by farmers, however it is of value to grazing livestock (Derrick *et al.*, 1983) and may be of greater value earlier in the grazing season and before flowering commences (McGhie *et al.*, 1983). Considering the literature, the dock herbage value is set in Table 6.1 at €65 t DM. However, changing the value of dock DM to the lower range of what McGhie *et al.* (1983) or Derrick *et al.* (1993) reported (i.e., 40% or 50% value of PRG) does not alter the economics or conclusions drawn on the basis of Table 6.2. above. The yield of the additional grass herbage is the most important factor in the calculation. However, if a farmer considered the contribution of the dock herbage DM to be valueless when assessing the benefits of EGH applications, then EGH applications become economically worthwhile.

The results of Chapter 3 are immediately applicable to the 75,000 ha of grassland that is reseeded each year in Ireland (Anon, 2019). Creighton *et al*. (2011) found that only 53% of reseeded grassland was sprayed with a NLH (called 'post-reseeding herbicide' in Creighton *et al*., 2011), even though 89% of the same cohort of farmers applied glyphosate to desiccate the old sward. Possible reasons as to why a greater proportion of the farmers in Creighton *et al*. (2011) did not apply a NLH could be due to lack of opportunity after an autumn reseed, lack of weeds present in the reseeded sward or a lack of knowledge of the benefits of a NLH. There is no survey data on the success of NLH's, which is an obvious area for further research.

In future, it is probable that farmers may have to prioritise their herbicide use to a limited number of applications. If limits are imposed on grassland herbicides, the results of Chapter 3 confirm that the most effective growth stage for the application of herbicides for dock control in grassland occur at the seedling stage in the first six months after reseeding and herbicide efficacy declines rapidly once the dock tap root becomes established. There is also significant opportunity to abide by future pesticide restrictions at the EGH timing but only if repeated applications of herbicides are applied in a targeted fashion (spot-spraying) using optical sensors and modified sprayers.

6.2. The role of K in dock competitiveness in grassland and implications for a dock management strategy

The literature reviewed in Chapter 2 was somewhat inconclusive in the relative importance of K for dock growth whether conducted in pots (Humphreys *et al*., 1999, Van Eekeren, 2006) or looking at field survey evidence (Peel and Hopkins, 1980; Humphreys *et al*., 1999; Harrington *et al*., 2014). There is, however, strong evidence that docks require and accumulate more K in their foliage than PRG grown in the same conditions (Wilman and Reilly, 1993; Humphreys *et al*., 1999). The results of Chapter 4 help clarify the role of K in various aspects of dock competitiveness in grassland and possible ways this can be combined in a dock management strategy.

Firstly, Chapter 4 showed that dock densities (in the initial two years after germination), were related to STK. This positive relationship, although weak, was very similar to the pot experiment results of Humphreys *et al.* (1999). Those authors found that dock foliage and root biomass (in the 18 months post germination) was reduced at lower STK when grown in competition with PRG. Therefore, the relationship in Chapter 4 probably resulted from establishment differences of the docks. Subsequently, once docks became well established (c. two years post germination), STK (or fertiliser K) has little or no influence on dock population density or clonal propagation rates, at least within the seven-year timeframe of this study and despite the large spread in STK levels recorded in Chapter 4.

The second conclusion of Chapter 4 is that fertiliser K applications did influence dock herbage and dock root DM production. The ANOVA table results (Table 4.5) need to be read in conjunction with the correlations (Table 4.4) as clearly there was strong competition between the grass and docks (as shown by the inverse relationships in Table 4.6), which was influenced by STK levels. The ability of fertiliser K to shift the balance between dock and grass DM production was evident at low fertiliser K application treatments (0 and 50 kg K ha^{-1}) and is the key observation from this study. Here the grass grew (satisfied its K requirements) to the detriment of the dock. This competitive effect of the PRG over the dock is a combination of the finer grass roots taking up the available soil K and the lower requirement of grass for K and agrees with the pot experiments of Humphreys *et al.* (1999). Similarly, Wulff *et al.* (1998) showed that sugar beet (with a root analogous to docks) was affected more by lack of K fertiliser than cereals (with a root system analogous to grass). At the high fertiliser K treatments in Chapter 4, both the grass and docks had adequate soil K levels available and grew unhindered, and it is likely the dock foliage contained more K than the grass but unfortunately this analysis was not conducted in the present study.

Thirdly, the mean weight of dock roots ha^{-1} growing in soils with moderate STK (<150 mg L^{-1}; 0, 50 and 100 K treatments) was 20 % lighter than where docks grew in soils with luxury STK (>150 mg L^{-1}; 150, 200, 250 and 300 K treatments). As a control mechanism, achieving a 20% reduction in dock root biomass per unit area from K fertilisation strategy compares favourably with the intensive defoliation strategy of Van Evert *et al*. (2020) who reduced dock root biomass by 20%. However, neither strategy (K fertilisation nor intensive defoliation) was as effective at reducing dock root DM production as the EGH treatments in Chapter 3 (dock root biomass was lowered by between 36% and 57%). Of course, the rapid reduction in dock foliage from intensive defoliation (Van Evert *et al*., 2020) and herbicide use (Chapter 3) is far more desirable and more profitable from a farmer's viewpoint than just reducing dock root biomass.

Humphreys *et al.* (1999) found that dock population densities were greater in both grazing and silage fields where STK were more than the grass crop's requirements (i.e., STK of between 70 and 150 mg L^{-1}). They postulated that this could be from the role K plays in the transport of assimilates from the leaves to the roots, thus favouring dock survival under field conditions. The results shown in Chapter 4 corroborate the findings of Humphreys *et al*. (1999) and present the strongest evidence thus far that K is an important nutrient for favouring the competitiveness of docks in grassland, especially the dock root.

6.2.1. Integrated Pest Management using K fertiliser

The fact that K fertiliser significantly affected dock root biomass is quite an important finding in designing a dock management strategy and has multiple applications. It is likely that the effect of K on root biomass is built up over several years, which needs to be accounted for when designing IPM experiments. Possible synergistic effects combining K fertiliser strategies with herbicides, defoliation strategies or root cutting are areas worthy of further study.

Chapter 3 (Table 3.4) showed that 2.5-year-old docks can recover from herbicide applications by producing new foliar growth from the roots and that recovery was inversely proportional to root biomass. Van Evert *et al*. (2020) also showed that intensively defoliating a dock plant depleted its reserves and the foliage re-growth was proportional to the root biomass. Dreyer *et al.* (2017) summarised the current understanding of the role of potassium as a sophisticated energy transfer system within plants but especially between plant shoots and roots. Potassium facilitates the communication of energy demands between shoot and root. So, it is logical to assume that interfering with the flow of assimilates between the root and shoot in docks (by fertiliser K strategies) would act synergistically with control mechanisms like cutting or herbicides. A reliable method to test starch and sugar contents in dock roots was developed by Decruyenaere *et al*. (2011) which would be useful to examine the root dynamics in K-deficient dock roots, especially in association with other control options. This is an area worthy of further study.

6.3. Can we reliably predict forward the population dynamics of seedling docks and their effects on grass herbage DM production?

Docks have been described as a 'follower of man' and 'relics' of previous soil disturbance events (Cavers and Harper, 1964). The evidence presented in Chapter 5 strongly supports this assertion. In Table 5.1 and Figure 5.5, 90% of the variation in dock m^{-2} in the autumn 2015 was explained by the variation in docks m^{-2} in spring 2013. There were also further correlations between initial dock numbers and all subsequent dock densities recorded. A seedling population density of as low as 0.6 docks m^{-2} can justify the cost of post-emergence herbicide from a solely economic perspective although there is considerable uncertainty around this number. Where post-emergence herbicides are not applied, every effort should be made to limit dock seedling numbers to not more than 1.0 m^{-2} in newly established leys.

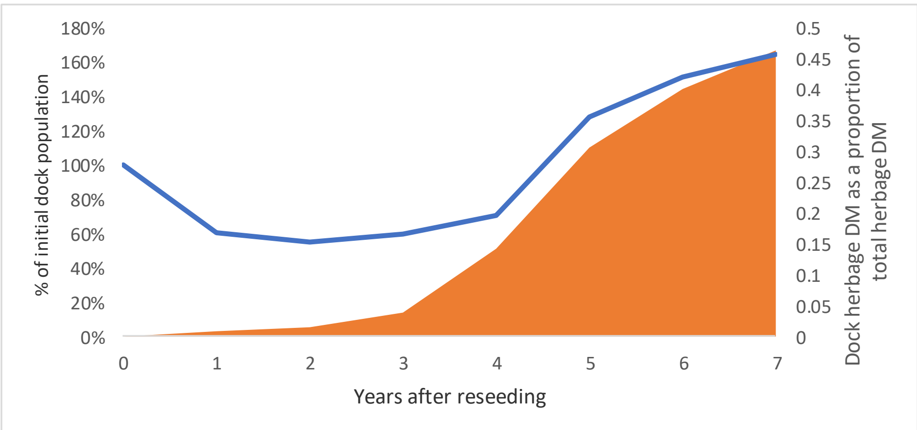
As can be seen in Figure 6.1 (below), docks undergo clonal propagation and significantly reduce grass growth from the 3rd year after germination. Chapter 5 demonstrated how the different types of clonal growth habit resulted in lower value grasses (primarily *A. stolonifera;* termed NSG) invade the space created by the dock competition. Certainly, beginning a dock control program after the docks have affected the composition of grass species in the swards (year six after reseeding) reduced the economic effectiveness of the control because PRG is a phalanx clonal species and was not as affective at filling in gaps left after controlling large dock plants.

Oswald and Haggar (1983) concluded that ground cover was a more accurate predictor of the effect of docks on grass herbage than dock number m^{-2}. This was not directly comparable to Chapter 5 as the work of Oswald and Haggar (1983) was in an eight-year-old grass ley and they avoided 'areas of poor grass growth' and it is likely that a proportion of the older docks were losing vigour and the 'areas of poor grass growth' were because of dock competition. Also, in the present study, the assessments of dock numbers were based on a rule that each dock ramet produced 4 leaves, assessed from a standing height, which was a good proxy to a ground cover assessment. This is also corroborated as by the strong relationships between subsequent dock assessments in Table 5.1. Oswald and Haggar (1983) reported that docks m^{-2} was an unreliable predictor for grass yield decreases. Chapter 5 shows docks m^{-2} to be strongly correlated to reductions in grass herbage DM (e.g., $r=-0.833$; $P<0.001$ in 2015; Table 5.2), at least in the seven years post reseeding. It is possible that these relationships could decline as but this was beyond the scope of the present study. If we look at the experiments in chapters 3 and 4; dock numbers did not change much between 2010 and 2012. The docks were small and had no big effect on PRG herbage production. From 2013 onwards, docks increased in numbers and in the size of individual plants. It is hard to disentangle the effect of dock numbers and the effect of dock ground cover in the present studies because both increased simultaneously.

6.3.1. Dock milestones following re-seeding

An additional outcome from this thesis is the development of benchmarks or developmental milestones in the dock's lifecycle, where the dock and grass sward developed in tandem following reseeding. This compliments our understanding of docks, their impact on grass and can act as a forecast tool for agronomists and farmers when planning management strategies or planning further experimentation on docks. Being able to 'map' the behaviour of weed populations is quite desirable from a weed management perspective and one of the key principals of Integrated Weed Management (Naylor, 2002; Harker and O' Donovan, 2013).

Figure 6.1 Dock numbers (line) as a proportion of the initial seedling population density and dock herbage DM production (stacked area) as a proportion of total sward herbage DM during each year. Data is from the control treatment in Chapter 3 and the 200 K treatment* in Chapter 4 (n = 16).



* Includes estimate of dock density in 2016

Figure 6.1 shows the % change in dock numbers m^{-2} expressed as a % of the initial seedling dock population and the proportion of dock herbage DM in the overall sward herbage DM between reseeding in 2009 (year 0) and the end of the current study in 2016 (year 7). To mimic the most likely scenario when farmers are establishing a new grass ley, this graph combines data from the 'control' treatment in Chapter 3 and the '200 K' treatment in Chapter 4 as both treatments have been treated in an identical manner from 2009 to 2016. To the best of our knowledge, this is the first time, a homogenous, naturally established dock population was monitored in such a fashion and as such is not relatable to previous experiments. However, these results do agree with individual components of Courtney (1985), Hopkins and Johnson (2002) and Hopkins and Johnson (2003). Firstly, the experiments of Courtney (1985) also monitored 'planted' docks for seven years and found that high dock densities (32 docks m^{-2}) depressed grass herbage production by 40% within two years of planting while modest dock densities (8 docks m^{-2}) did not have the same effect on grass until four years after planting. The experiments of Hopkins and Johnson (2002) and Hopkins and Johnson (2003) were conducted on the same population of docks established by transplanting into disturbed patches. In the first year after transplanting, their mean dock population density of 15.7 docks m^{-2} comprised 0.9% of the total herbage; 4.6 % in year 2; 17.4 % in year 4; 31-35% in year 5; and 50% of the total herbage production in year 6 after transplanting.

Broadly speaking the dock lifecycle can be broken into 3 stages:

Stage 1: germination and initial establishment occurs within the first year however, dock seedling numbers can decline by up to 50% (Chapter 5).

Stage 2: establishment and juvenile growth happens during years 2-3 during which time dock numbers remain static (Chapter 5). Root reserves increase during this stage and new shoots are developing (Pino *et al.*, 1995). Docks can comprise up to 5% of total sward DM in this period (Hopkins and Johnson, 2002).

Stage 3: clonal propagation happens from years 3-6 during which time dock numbers m^{-2} increase rapidly and this corresponds when docks significantly impact on grass growth and influence sward composition (Chapter 5).

6.3.2. Recent changes in Irish grassland farming and future study

Since this study was conceptualised in 2010, several developments have occurred that impact greatly on Irish grassland farming. Firstly, the reality of the world's changing climate and weather systems (climate change) is undeniable (UN, 2022 & IPCC, 2021) and is arguably the major driver of recent EU agricultural policy (Anon, 2020a). Secondly, milk quotas have been abolished across the EU, resulting in a significant (37%) increase in Irish dairy cow numbers since 2011 (ICBF, 2021). Most recently, the unprecedented rise in fertiliser prices because of unreliable energy supply (ultimately because of the Russian invasion of Ukraine) has called to question the entire agricultural supply chain and raised food price inflation across the world (Butler, 2022 & FAO, 2022).

Combining these developments has meant there is a growing requirement for farmers to produce more food while reducing inputs and avoid negative impacts on the environment. This approach is often referred to as sustainable intensification (Reheul et al., 2017).

Section 2.1 discussed how grazed grass (based on high yields of perennial ryegrass receiving artificial fertilisers) underpins output from ruminants in Ireland and any threat to this production must be manged. However, given the rise in fertiliser prices, the economic sustainability of such monoculture systems may become questionable. An old solution, once widespread in Irish pastures (O' Sullivan, 1982) is now once again proving its worth in this new paradigm that agriculture finds itself in. Multi-species grassland swards are reported to have yield advantages over grass monocultures, particularly at low rates or zero inorganic N application (Connolly *et al*., 2009) and supress unsown species or weeds (Connolly *et al*., 2018).

Chapter 3 showed that an established monoculture PRG sward is extremely effective at preventing dock seedling germination and establishment. However, Chapter 5 showed that once docks establish during reseeding, the same PRG sward is subsequently a suitable environment for dock herbage DM production and recruitment of new dock ramets through clonal propagation. Can we add components to the initial sward mixture (or the mature sward) that limits these effects of docks? From an ecological perspective, monocultures of PRG swards leave vacant niches that weeds can exploit. Thus, by adding a legume or a forb to the reseeding seed mixture could greatly reduce the ecological space available to docks compared to a PRG monoculture (Connolly *et al*., 2018). This could reduce dock seedling establishment during pasture reseeding (which has long lasting consequences; Chapter 5) and possibly reduce the docks' ability to recruit new ramets through clonal propagation and/or limit its the impact on the grass sward (Chapters 3 and 5).

Another interesting concept to examine is the relative competition stresses grass and other species exert on various life stages of docks. Numerous authors have shown that increasing the cutting frequency of a PRG sward reduces the dominance of docks in the sward (Courtney 1985; Hopkins and Johnson, 2002) but does not eliminate them (Van Evert *et al*., 2020). In contrast, Martinkova *et al*. (2009) has shown that dock numbers m^{-2} and dock biomass were significantly reduced and eventually eliminated in an unmanaged sward consisting of *Elymus repens* and *Festuca rubra*. Hann *et al*., (2012) examined management intensity in a PRG sward but found little effect on the docks within the three-year timeframe of their study. What processes are occurring in unmanaged areas that eliminate docks? Perhaps, PRG roots are not competitive against docks whereas the roots of other grass species are. For example, PRG has been shown to have a lower root biomass than *Festuca arduninacea* (Cougnon *et al*., 2013). It is also possible that docks in unmanaged areas suffered from a lack of potassium or the competitive advantage docks have from their tap root (section 2.4.2) is not relevant when the sward is not cut. The study area of belowground plant ecology has developed rapidly in recent years and is considered quite important in terms of carbon sequestration and sustainable agriculture and including docks in a larger study may develop new insights to help manage docks.

6.4. Final conclusions

The overall conclusion from this thesis is that sustainable dock control is more likely achieved by using IWM principles. In essence, this means combining knowledge of the docks' biological and ecological behaviors with good agronomic practices. The three key findings of the thesis and examples of IWM are:

- Prioritise the application of a new ley herbicide (NLH) after reseeding (but before the seedling dock develops a tap root). This can result in five years dock free grass swards as it exploits the grass sward's inherent ability to prevent subsequent dock seedlings establishing.

- Secondly, avoid excessive soil potassium levels (STK above 110 mg L^{-1}) in a dock infested sward. This will reduce dock herbage production and a corresponding increase in grass herbage production. This STK level will also reduce dock root biomass over time and reduce dock seedling establishment after reseeding.

- Lastly, dock seedling populations of 1 dock m^{-2} or greater are sufficient to justify a NLH. Seedling docks are the founding population from which docks expand their numbers through clonal propagation (occurs in years three to four after reseeding). This rapid expansion in dock numbers occurs in parallel with a rapid increase in dock herbage production. This combination of increasing dock numbers and increasing dock herbage production competes with the grass sward, reducing its production by up to 50% and reducing the proportion of PRG in the sward.

The key findings of this thesis are immediately applicable to any grassland farmer and will improve dock management on that farm. Also, the findings of this thesis are in keeping with the principles of IWM and the proposed pesticide legislative changes. Thus, it is possible to reduce overall pesticide applications and improve dock control.

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