Non-chemical management of docks (Rumex)

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1. Introduction: when is a weed not a weed?

Docks, mainly the broad leaved dock (*Rumex obtusifolius*) and the curly dock (*Rumex crispus*) are common weeds in cooler and wetter climates. They are predominantly a weed of pasture, especially long term pasture, because regular tillage / cultivation kills them so they don't survive in cropping systems. They have in the past been proclaimed as highly problematic weeds, even being listed in noxious weed legislation e.g., in the Republic of Ireland[1] and the United Kingdom[2]. However, this is considered a clear example of overestimating the negative impacts of particular weeds and an outdated definition of weeds.

Fundamentally, a weed is a value judgement of the positive and negative attributes of any given individual and/or population of plants at a given point in time. Typically in agriculture, the value judgements are ultimately economic, i.e., does any particular plant, or population of plants impact farm profitability. If the answer is no, the plant or population of plants are not weeds. In many cases the economic impact of weeds has never been properly calculated, resulting in the view, as evidenced by noxious weed acts, that even one weed is too many, and total eradication is required. This is a foolish view, especially where the weeds are in their native range and are impossible to eliminate. For example, studies in Ireland, pastures with 15% or less ground cover of docks will produce more total dry matter than the same pasture without docks (Courtney, 1985). Docks are palatable, unlike toxic weeds such as ragwort (*Jacobaea vulgaris*), dock foliage has higher potassium, zinc, magnesium and tannin levels than grass, has been found to prevent bloat, and shoots of *R. crispus* in young stages have a good nutritive value for cattle (Courtney, 1972; Humphreys, 1995). Moderate populations of docks therefore do not impact farm economics, and may even benefit stock and therefore profits, so therefore should not be considered weeds, but rather natural components of farm ecosystems. However, large dock populations have clearly been shown to be detrimental, so, they do need to be managed, but, not controlled.

Beyond farm profitability, docks are hosts for a wide range of other species, particularly insects, so in their native ranges, and potentially even where they are exotics, they contribute to biodiversity and ecosystem functions. For example, docks are a dominant food source for the green dock beetle (*Gastrophysa viridula*) (Figure 1) and the seed is important to a range of seed feeders including invertebrates such as beetles. The importance and benefits of weeds is being increasingly recognised (e.g., Gerowitt *et al.*, 2003; Marshall *et al.*, 2003; Blaix *et al.*, 2018; Storkey & Neve, 2018) and[3], so at an ecological level elimination of docks from farms is also undesirable.

The aim of dock, and other weed, management in modern farming should therefore be to manage weeds to economic thresholds, rather than aiming for their complete eradication.

[1] https://www.agriculture.gov.ie/farmingsectors/crops/controlofnoxiousweeds/
[2] http://www.legislation.gov.uk/ukpga/Eliz2/7-8/54
[3] http://www.arc2020.eu/unplanned-vegetation-is-important-aka-weeds-provide-for-needs/

Figure 1. The green dock beetle (*Gastrophysa viridula*). Larvae skeletonising a leaf (left) adults (right)

2. Dock management

Non-chemical control of any weed requires a systems based / integrated approach. The metaphor of ‘many little hammers’, coined by Liebman & Gallandt (1997), highlights that multiple tools are needed. To work out which tools will be effective and how to use them it is essential to understand the biology and ecology of weeds.

2.1. Key components of dock biology and ecology

Docks are rosette-forming, herbaceous perennials, consisting of a crown (short, vertical, underground, true stem), with large fleshy tap roots (true root, Figure 2).

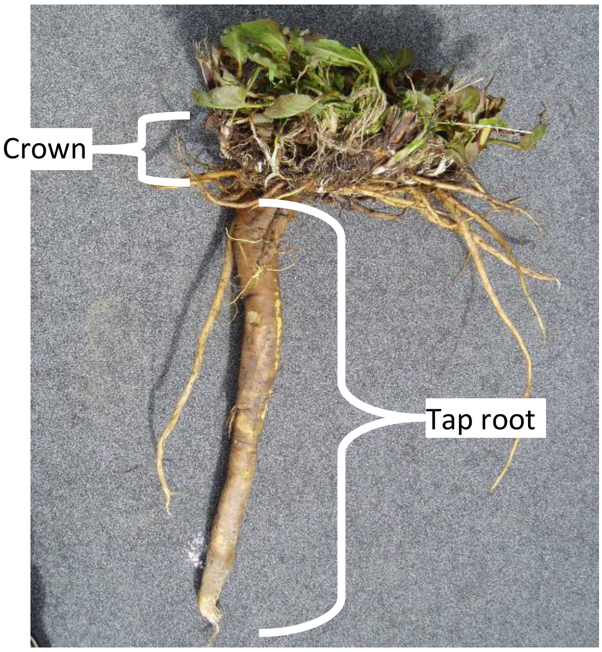

Figure 2. Dock plant showing regrowing leaves, the crown, main large tap root and smaller roots sprouting from daughter crowns.

Leaves and flower stems are produced from the crown. The main means of reproduction are via the large numbers of seeds that are produced, but, docks can also produce clones via offshoots from the crown, though the number of new plants produced this way is insignificant, especially as the parent plants also tend to die off.

There is however, significant confusion, both among land managers and scientists, about the ability of docks to regenerate following disturbance, e.g., tillage / cultivation or digging up. Only the buds (meristems) in the leaf axils of the true stem are able to dedifferentiate to produce roots. The true root is unable to dedifferentiate so it cannot produce shoots, so it is only the crown that can regenerate, as it is true shoot material. However, in some cases the crown and root can appear quite similar (Figure 3), especially as the crown produces adventitious roots, which may be partly to blame for the confusion about whether roots can regenerate as some people may confuse the crown for true roots.

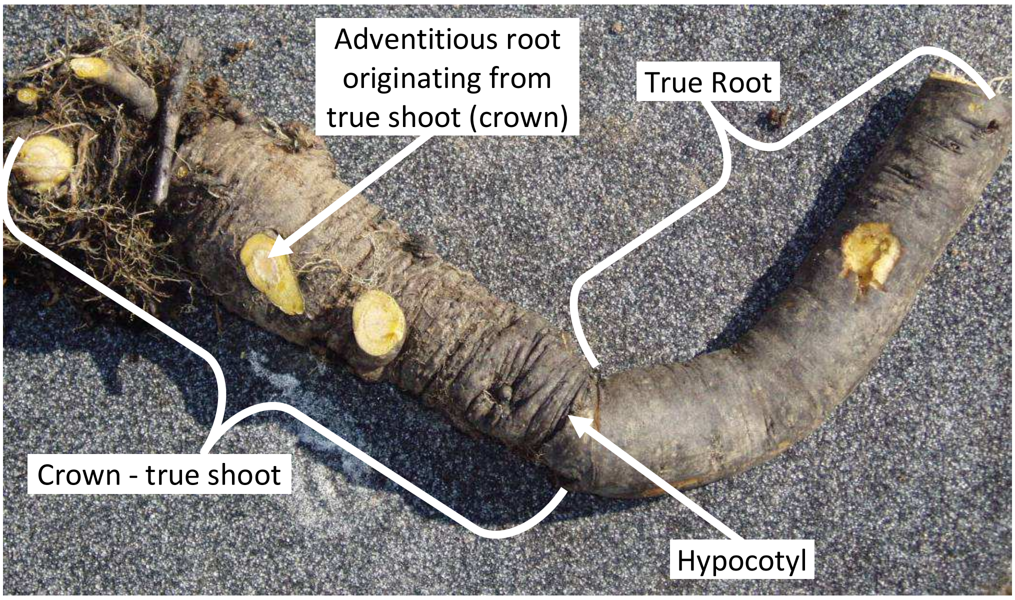

Figure 3. Section of dock showing the visual similarity between crown and root.

As a comparison, docks are morphologically identical to rhubarb (*Rheum rhabarbarum*), both being in the Polygonaceae. Rhubarb also only regenerates from the crown - which is why rhubarb is vegetatively multiplied by splitting the crown, not the root.

Docks try to maintain a root shoot ratio around 75% root 25% shoot, with higher root percentage overwinter and lower when flowering. Removal of foliage causes the dock to withdraw root reserves to re-establish root:shoot ratio, which takes about four weeks. Therefore defoliation intervals less than four weeks results in a reduction in plant size as the root reserves are continually used to replace the foliage. In comparison defoliation intervals grater than four weeks allows docks to accumulate carbohydrates in their roots, with increasing rates of accumulation with increasing defoliation interval, therefore defoliation intervals greater than four weeks allows docks to become more competitive with pasture.

Dock seeds need light to germinate so can only establish on open soil, not under good pasture covers. It also needs regular diurnal temperature fluctuations to germinate, so, is less likely to germinate in winter. Dock seedlings are weak competitors until about 40 to 50 days old at which point the seedling root swells into a tap root and the crown forms. After this point their competitive ability increases rapidly becoming very high after six months of age.

2.2. Pasture management

Managing any pasture weed is almost entirely down to pasture management. Good pasture management is based on four key principles:

- Healthy soil, based on optimum pH and nutrient levels, and good structure;
- A highly diverse sward, comprising multiple species of grass, legumes and forbs;
- Short grazing duration, long return period, rotational grazing;
- Minimising soil compaction.

A healthy soil is the foundation of all farming. A soil with nutrient deficiencies or incorrect pH will not support optimum pasture growth, allowing weeds that can tolerate, or are even adapted to, sub-optimal conditions, to out compete pasture species. Good soil structure is vital for optimum root growth, holding onto moisture while also allowing soil to drain freely, which compaction, whether from farm vehicles or stock, destroys. Observation of docks on farms shows that they often appear in wet and waterlogged areas of fields, though research on this is lacking, so it is not clear if they prefer wet areas or are more tolerant of waterlogging than the pasture species, so gain a competitive advantage. Regardless, improving drainage through reliving compaction, artificial drainage, and improving soil structure are all important remediation tools.

The common view in farming since the second world war has been that to maximise yield the species or cultivar with the highest yield was identified and then grown in monoculture. This view is increasingly being challenged (Weigelt *et al.*, 2009; Sturludóttir *et al.*, 2014) and [4]. From an ecological perspective monocultures have many vacant ecological niches that are ripe for weeds to take advantage of. By having multiple species of each of the three key pasture components, i.e., grasses, legumes and forbs (e.g., plantain and chicory), the amount of vacant ecological space is significantly reduced, decreasing the space available to weeds. Further, different species grow at different times of year, so, ensuring that the ecological space is full all year round.

Likewise, having species filling different ecological niches means having multiple species can produce higher yields than monocultures (Wendling *et al.*, 2017). From the animal perspective, it is increasingly realised that simplified pastures with only a few species, while providing sufficient dry matter for the animal, fails to provide the diversity of diet animals need to truly thrive and perform well.

The traditional grazing method, called set stocking, spreads the animals around the farm so all pastures are being grazed most of the time. This creates the problem that the stock preferentially eat the most palatable species, grazing them out, and leaving the unpalatable species alone, allowing them to prosper due to the reduced pasture competition. Also, plants keep their root and shoots in balance, so when a plant is continually grazed, it only has a small root system, which coupled with a small amount of leaf, means it can only grow slowly. The alternative to set stocking is rotational grazing, which has the stock in large herds which only feed on one field, or part of a field, for a few days, or even just a few hours, before being moved on to new pasture. This gives the pasture time to grow lots of leaves to capture sunlight and a large root system to capture water and nutrients. After it is grazed, it then has the resources in the large root system to quickly regrow new foliage in the absence of further grazing, thereby maximising forage production. This also means that pasture strongly competes with weeds. Further, with rotational grazing, stock are less able to pick and choose what they eat, so, they tend to eat everything, including the weeds, unless they are toxic or highly unpalatable. In such situations, most livestock will eat docks, thereby setting them back.

After incorrect nutrient levels, soil compaction is the second most important factor impacting pasture (and crop) productivity. It is not just large tractors that cause compaction, even small livestock such as sheep, will cause compaction when the soil is in a plastic (wet) state. It is therefore important to have strategies and systems in place to avoid having stock on fields when they are in the plastic phase and susceptible to compaction. However, docks are most problematic in the colder, wetter higher latitudes, where the soil can be in the plastic state for many months over winter. In many cases, stock are already housed over winter because of this, but, a renewed emphasis on compaction management at all times of year is required, e.g., having the resources to move animals to the sheds, even in summer, when there is heavy rain.

[4] http://www.the-jena-experiment.de

2.3. Mixed grazing

Stock species are well known for their varying acceptance of docks. Deer are the most tolerant even liking docks, with goats and sheep next which will eat younger foliage, and being browsers, goats like the woody flower spikes. These are followed by cattle who will eat docks, especially if hungry (Figure 4), while horses avoid docks as much as possible. Where practical, cross grazing dock tolerating species with intolerant species can assist with keeping docks suppressed.

Figure 4. Beef finishers eating offered broad leaf docks plants while waiting to be moved to new pasture.

2.4. Nutrient management

A number of alternative agriculture advocates claim soil nutrient levels are key drivers of weeds. However, there is exceptionally little research data to back up their claims, and, the conceptual models of how nutrient levels drive weed populations have not even been formulated, e.g., does the weed have a higher requirement for specific nutrients, or able to tolerate excess or deficient levels, what are the impacts on inter-species competition, is there an effect on seed quality, or germination, etc. However, a significant amount of research on the impact of nutrients on docks was undertaken by Dr James Humphreys in the Republic of Ireland (Humphreys, 1995; Humphreys *et al.*, 1999).

The research clearly showed that potassium (K) is a key driver of dock persistence because docks have a higher requirement for K than grass as it is used to drive the partitioning of carbohydrates between roots, leaves and flowers. Where soil K levels are at or below optimum, grass, with its highly competitive fibrous root system, will out-compete docks for K, thus inducing K deficiency in the docks stunting and making them less competitive. Once soil K levels are above optimum, docks have free access to the excess K, because grass does not have luxury K uptake, so it only takes up the amount of K it needs, so docks get all the excess K to themselves. Therefore, the higher soil K levels are above optimum, the stronger and more persistent docks will become. Established docks are also highly competitive with pasture through shading from their leaves, thus reinforcing the effect of high K levels.

The simple lesson from this is potassium levels must be kept at or below optimum. The standard cause of excess K levels on livestock farms is due to slurry and farm yard manure (FYM) application to the fields closest to the yard. It is essential that soil nutrient tests are regularly undertaken (every three to five years), the nutrient content of each batch of manure is tested, and manure only added where it will not bring any nutrient level above optimum, but particularly for nitrogen, phosphorous and potassium (NPK).

Humphreys also found a strong interaction between soil nitrogen (N) levels, defoliation frequency and dock populations. At defoliation frequencies less than four weeks higher N levels favours grass, at lower defoliation frequencies higher N favours docks. So rotational grazing and harvest of conserved feed, e.g., silage, should be focused on a return period of a month or less, especially during the main growing season, and nitrogen must never be over applied, e.g., it is best in multiple small applications than large single applications.

2.5. Silage and grazing fields

Fields that are predominantly used for silage often have high dock levels. The key reasons for this are not due to the return of large numbers of dock seeds in slurry to silage fields, as is commonly believed. This is because the first cut of silage typically occurs before seeds are set, so few seeds get into the main bulk of silage. Dock seeds are killed by the ensiling process due to low pH. Rumen digestion also kills a significant amount of seed, as does slurry. So there are multiple reasons why slurry contains zero viable dock seeds.

The key reasons silage fields have high dock populations because they are typically close to the farm yard so they are convenient site for slurry applications, and as silage is coming off they have the highest need for nutrient replacement, so they often receive large amounts of slurry. Slurry is high in K, and, as discussed in section 2.4, high K levels increase dock persistence. Also silage fields often have high levels of N, which coupled with infrequent cutting, also favours docks. And, silage cut close to the ground often results in bare exposed soil, which is what docks require to germinate. Silage fields are therefore almost optimally managed for high dock populations!

The key solutions to this are to ensure N and K levels never exceed optimum, through regular soil tests, e.g., every three years, and only applying slurry according to tests. And, where possible to rotate grazing and silage fields, so the shorter term rotational grazing (less than a month return time), starts wearing the docks out.

2.6. The role of seedbanks

Much is made of the longevity of seeds, however many of these studies keep seeds in ideal conditions, typically under a controlled climate. In comparison, soil is a highly hostile environment for seeds, being abrasive, chemically caustic and teeming with living things from microbes to vertebrates that view seeds as a highly nutritious food source. Therefore persistence in soil is far less than seeds potential longevity. It is therefore far more valuable to focus on the half-life of the weed seed bank, which, compared to decades for longevity, can be as little as one year (Roberts & Feast, 1972; Gallandt, 2006; Gallandt *et al.*, 2010; Mirsky *et al.*, 2010).

Much is also made of the very large numbers of seeds that weeds, such as docks, can produce, with 60,000 seeds for broad leaved dock being a common figure. However, like seed longevity, this is the maximum seed production under optimum conditions (e.g., large undisturbed plant), and in a well managed pasture, with frequent rotational grazing, with strategic mowing to remove flower stems post grazing, seed production will be a fraction of this, even zero. However, as little as 600 seeds per plant are required to maintain a seedbank of 12 million seeds, which may sound large, but equates to 1,200 seeds per square meter, the vast majority of which, e.g., 90% will be unable to germinate due to being too deep in the soil, dormant, etc. leaving just 120 seeds per square meter able to establish if conditions are right. This population is also tiny compared to arable weeds, such as fat hen (*Chenopodium album*) which can have 12,600 seeds per square meter (Rahman *et al.*, 2006). Humphreys (1995) concluded that due to dock seeds needing direct sunlight to germinate, in a well managed pasture, it would be highly unlikely for many docks to be able to establish, and therefore, most docks in a pasture have been there since establishment. It is therefore considered that the dock seedbank is only truly relevant when pasture is established.

A core component of any non-chemical weed management strategy for controlling therophyte weeds (weeds that survive winter as seeds) is minimising weed seed rain, to reduce the size of the weed seedbank. Dock's have a mixed strategy of being a perennial, particularly the broad leafed dock, and also produce a large amount of seed, which is their main form of reproduction and dispersal. Therefore a vital long-term strategy is to minimise the weed seed rain from docks by stopping them producing seeds by cutting or grazing off the flower stems. The best time to do this is just when they have started flowering because this results in the greatest loss to the plant. However, dock seed becomes viable very rapidly after flowering starts, with 15% viability six days after the end of the first flowering rising to over 90% after 18 days. It is therefore essential not to leave cutting or grazing of flowering stems too long or viable seed will have set. When the flower stem is cut off, the plants will try to flower again, especially in warmer regions, so these second flush of flower stalks also need controlling.

2.7. Dock management at pasture establishment

As the main route for docks into well managed pasture, is at establishment, it is clearly a critical point for dock management. There are some well established techniques to minimise docks establishing into new pasture. The key is to get the pasture established and achieving ground cover as quickly as possible to suppress dock seed germination, through light interception, and then to out compete the docks while they are still young and uncompetitive.

The same as for pasture management, correct pH and nutrient levels are key to ensure the pasture seedlings can thrive. A good seedbed is also critical. Where time allows, the use of false seedbeds (Merfield, 2015), is an exceptionally valuable technique. Only establish pasture at optimum times of year, i.e., when the soil and weather are warm, not cold and wet, to ensure rapid growth. Having a large number of pasture species, especially legumes and forbs with large leaves that quickly cover and shade the soil is particularly valuable. Higher seeding rates can also contribute to faster ground cover. Cattle slurry has also been shown to inhibit dock seed germination but not grass and this can be used to give the pasture a competitive edge (Humphreys, 1995).

2.8. Biological control

Biological control comes in three forms:

- Importation or classical;
- Augmentation;
- Conservation.

Importation involves importing a pest's natural enemies to a new locale where they do not occur naturally. Augmentation involves the supplemental release of natural enemies that already occur in a particular area, boosting the naturally occurring populations. This is further sub-divided into inoculative where a small starter population is released which reproduces and builds its population and inundative where very large numbers of an organism are released to swamp the pest. Conservation biocontrol aims to boost natural enemies that already exist in the environment, by making the environment more hospitable for them, for example for beneficial insects providing nectar and pollen through addition of flowering plants.

Biological control of docks in Eurasia is difficult because they are in their native range. Importation biocontrol is best suited to a exotic pest that lacks its predators from its native range, and even then, success, defined as reduction of the weed below economic levels, is only achieved in 10% of cases. Conservation biocontrol, is challenging, because docks already have a large number of species that attack them, so, finding an ecological manipulations that would significantly boost a sufficient number of dock pests to meaningfully decrease dock populations is particularly hard.

Augmentation, particularly inundative, using microbes has potential as there are species of pathogenic fungi that are specific to docks e.g., *Uromyces rumicis.* Specificity is very valuable as it means the microbe can be broadcast sprayed to kill docks without killing other pasture species. But, globally the development of mycoherbicides (fungi based herbicides) has been very challenging, and, has mostly been focused on weeds in high value cropping systems due to the cost of the final products. Less than a handful have proved practical and economic, so developing one for docks is considered unlikely.

Inundative augmentation with invertebrate dock pests, e.g., Fiery Clearwing (*Pyropteron chrysidiformis*) or the green dock beetle has potential, but, the challenges are considerable, including developing mass rearing systems and then scaling those up to commercial levels. Then distributing the live insects to farmers, getting them to lay sufficient eggs so the larvae kill or suppress enough docks to make an economic difference, all while keeping costs sufficiently low to so it is economically viable at the lower per hectare returns of livestock farming, are all considered exceptionally challenging.

2.9. Physical control

Livestock production has among the lowest gross margins of all types of farming (e.g., compared with arable and vegetable crops), and it, often occurs on hilly land that is less or unsuited for machinery access, so often it is not financially viable to spend money on direct / physical control techniques of docks. However, there are some situations where it is justified. For example, as most docks get into pasture during establishment, reducing dock numbers once the pasture is fully established, e.g., six months to a year after seeding, can pay dividends if the pasture is kept for many years, as the benefits of removal accrues year on year.

2.9.1. Direct dock plant removal

The key to effective physical control of docks is that they can only regenerate from the crown (true shoot), not the true roots. Typically the crown only extends five centimetres below the soil surface, and rarely as deep as 10 cm, therefore as long as the crown is removed then the root will eventually die. However, the ability of the crown to regenerate by producing new roots and shoots is prodigious, so the dug up crown must be prevented from re-establishing at all costs. In hot dry weather, especially if there is a good thickness of pasture to keep the crowns off the soil, they can just be left on the field to desiccate and die. In less than ideal drying conditions, the crowns will need to be taken off the field and destroyed, e.g., through composting or putting into slurry pits. The main tool for digging the crowns up is the 'dock fork' (Figure 5) which consists of two prongs and a pivot point to ensure a vertical clean lift and ease of use / good ergonomics.

Figure 5. Traditional dock fork (left), modern ergonomic design with interchangeable heads www.lazydogtools.co.uk (right).

2.9.2. Electrothermal

The other potential means of direct dock control is electrothermal weeding (Merfield, 2016). This technology was widely researched in the 1980s but lost out to herbicides, particularly weed wipers. It is now commercially available again due to the demise of herbicides. Its value lies in its systemic weed kill, due to the electricity flowing through the foliage and into the root system before dispersing into the soil, in the same way as systemic herbicides. The key requirement is that the weeds need to be higher than the crop, so the electricity can be selectively applied to the weeds. Electrothermal therefore has considerable potential for pasture weed management as a large majority of pasture weeds overtop the pasture, especially post low intensity grazing. Electrothermal is both systemic and selective for tall pasture weeds, an accomplishment that even herbicides cannot achieve.

Some informal testing of electrothermal has shown that for large established docks, it will take two or three treatments to fully kill the crown, but, for younger plants, e.g., up to one to two years old, a single treatment should suffice.

Electrothermal uses massively less energy than flame and steam weeders, with a greater than twenty fold lower energy use, and where plants are sparse, even lower use, as power is only used when the machine contacts a weed. Very large machines were developed in the 1980s, some over six meters wide, so, it is possible to have significant works rates. There are also hand held machines for spot treatment, so, it is hoped that within a few years this technology will become widely available to farmers, both to own, and for contractors to supply as a service.

2.9.3. Other techniques

A wide range of other techniques for direct dock control, such as thermal using flame and steam, mechanised dock diggers, etc. have been trialled. However, due to the need to kill the crown, which is buried in the soil, flame and steam require large amounts of energy making them uneconomic, and, mechanical approaches with their high capital cost and lower agility are considered unlikely to match a fit weeding gang using well designed dock forks both for speed and cost.

2.9.4. Renewing pasture with high dock populations

Where dock populations are large, it is likely to be cheaper to terminate the pasture and re-establish it rather than try and remove the docks. Typically, shallow (5 to 10 cm), powered cultivation with a rotovator should be used initially to detach and break up the crowns. Draft tools can also be used if available, e.g., vegetable undercutter bars. The crown fragments will vigorously regrow unless the soil and weather is particularly dry, so follow up tillage to stop the fragments re-rooting every one to two weeks will be required. This can be done with tined cultivators and harrows rather than power tools to preserve soil structure. This follow up is utterly critical because if the crowns are not killed the initial cultivation will create many more dock plants by dividing the crowns, just like for rhubarb! Tined cultivators also tend to drag the crowns to the surface where they will more quickly desiccate. If the crowns are completely killed through desiccation no further cultivation will be needed. If after a couple of passes they are still viable but weakened, they can be ploughed down, ideally fairly deeply, to kill then through light starvation. Ploughing intact docks does not always guarantee success, because if the plants are large, they can send up shoots through a considerable depth of soil, and re-establish themselves (Figure 6).

Figure 6. Dock plant that has been ploughed under, and then put up a shoot from the buried crown, that has then established a new crown and leaves. Note the elongated bamboo like appearance of the shoot that grew to the surface and that adventitious roots are only produced from the stems nodes, not internodes, and that the true root did not produce shoots, indeed it has died.

3. Conclusions

The zero tolerance approach of the now failed 'war on weeds' must give way to a new focus on the long-term economics of weed management. For dock management, a low population of docks should be tolerated, based on the knowledge that controlling all dock plants is a waste of money, and, they are an important part of the natural biodiversity of Europe. Effective non-chemical dock management is almost entirely down to good pasture management: the management of the soil, the pasture plants themselves and how they are grazed. A long-term view is required, up to a decade, to gradually reduce in-field dock populations and the weed seedbank that infests new pastures with dock seedlings.

4. References

Blaix, C., Moonen, A. C., Dostatny, D. F., Izquierdo, J., Corff, J. L., Morrison, J., Redwitz, C. V., Schumacher, M., Westerman, P. R. & Rew, L. (2018). Quantification of regulating ecosystem services provided by weeds in annual cropping systems using a systematic map approach. *Weed Research, 58*(3), 151–164. https://onlinelibrary.wiley.com/doi/abs/10.1111/wre.12303

Courtney, A. D. (1972). *Docks in grassland, their influence on herbage productivity.* Proceedings of the Proceedings of the 11th British Weed Control Conference, London, UK, 315-322.

Courtney, A. D. (1985). *Impact and control of docks in grassland.* Proceedings of the Occasional Symposium of the British Grassland Society, Croydon, UK, 120-127.

Gallandt, E. R. (2006). How can we target the weed seedbank? *Weed Science, 54*(3), 588-596. https://doi.org/10.1614/WS-05-063R.1

Gallandt, E. R., Halloran, J., Kersbergen, R., Mallory, E. & Sideman, E. (2010). *Managing weed seed rain: A new paradigm for organic and low-input farmers*. Washington, Maryland, USA: Sustainable Agriculture Research & Education (SARE). https://projects.sare.org/project-reports/lne06-237/

Gerowitt, B., Bertke, E., Hespelt, S. K. & Tute, C. (2003). Towards multifunctional agriculture - weeds as ecological goods? *Weed Research, 43*(4), 227-235. http://www.blackwell-synergy.com/doi/abs/10.1046/j.1365-3180.2003.00340.x

Humphreys, J. (1995). *Investigations into aspects of the dynamics of Rumex obtusifolius L. (Broad-leaved dock) populations in grassland.* PhD, University College Dublin, National University of Ireland, Dublin

Humphreys, J., Jansen, T., Culleton, N., Macnaeidhe, F. S. & Storey, T. (1999). Soil potassium supply and *Rumex obtusifolius* and *Rumex crispus* abundance in silage and grazed grassland swards. *Weed Research, 39*, 1-13.

Liebman, M. & Gallandt, E. R. (1997). Many little hammers: ecological management of crop-weed interactions. In L. E. Jackson (Ed.), *Ecology in Agriculture* (pp. 291–343). San Diego, CA: Academic Press

Marshall, E. J. P., Brown, V. K., Boatman, N. D., Lutman, P. J. W., Squire, G. R. & Ward, L. K. (2003). The role of weeds in supporting biological diversity within crop fields. *Weed Research, 43*(2), 77-89. http://www.blackwell-synergy.com/doi/abs/10.1046/j.1365-3180.2003.00326.x

Merfield, C. N. (2015). False and Stale Seedbeds: The most effective non-chemical weed management tools for cropping and pasture establishment. *The FFC Bulletin, 2015*(V4), 25. http://www.bhu.org.nz/future-farming-centre/information/bulletin/2015-v4/false-and-stale-seedbeds-the-most-effective-non-chemical-weed-management-tools-for-cropping-and-pasture-establishment

Merfield, C. N. (2016). Back to the future - electrothermal, systemic, weedkiller. *The FFC Bulletin, 2016*(V1) http://www.bhu.org.nz/future-farming-centre/information/bulletin/2016-v1/back-to-the-future-electrothermal-systemic-weedkiller

Mirsky, S. B., Gallandt, E. R., Mortensen, D. A., Curran, W. S. & Shumway, D. L. (2010). Reducing the germinable weed seedbank with soil disturbance and cover crops. *Weed Research, 50*(4), 341-352. http://dx.doi.org/10.1111/j.1365-3180.2010.00792.x

Rahman, A., James, T. K. & Grbavac, N. I. K. (2006). Correlation between the soil seed bank and weed populations in maize fields. *Weed Biology and Management, 6*(4), 228-234. http://www.blackwell-synergy.com/doi/abs/10.1111/j.1445-6664.2006.00223.x

Roberts, H. A. & Feast, P. M. (1972). Fate of seeds of some annual weeds in different depths of cultivated and undisturbed soil. *Weed Research, 12*(4), 316-324. https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1365-3180.1972.tb01226.x

Storkey, J. & Neve, P. (2018). What good is weed diversity? *Weed Research*https://onlinelibrary.wiley.com/doi/abs/10.1111/wre.12310

Sturludóttir, E., Brophy, C., Bélanger, G., Gustavsson, A. M., Jørgensen, M., Lunnan, T. & Helgadóttir, Á. (2014). Benefits of mixing grasses and legumes for herbage yield and nutritive value in Northern Europe and Canada. *Grass and Forage Science, 69*(2), 229-240. http://dx.doi.org/10.1111/gfs.12037

Weigelt, A., Weisser, W. W., Buchmann, N. & Scherer-Lorenzen, M. (2009). Biodiversity for multifunctional grasslands: equal productivity in high-diversity low-input and low-diversity high-input systems. *Biogeosciences, 6*(8), 1695-1706. https://www.biogeosciences.net/6/1695/2009/

Wendling, M., Büchi, L., Amossé, C., Jeangros, B., Walter, A. & Charles, R. (2017). Specific interactions leading to transgressive overyielding in cover crop mixtures. *Agriculture, Ecosystems & Environment, 241*, 88-99. http://www.sciencedirect.com/science/article/pii/S0167880917301135