Figure 9.1 - *Ageratina adenophora* (crofton weed) supresses growth of tree seedlings over vast areas of upland northern Thailand. It is one of many invasive exotic weeds that threaten the success of forest restoration. Insert: the rust fungus, *Baeodrum eupatorii*, is a potential biological control agent (Photo courtesy of Dr. Louise Morin)

Figure 9.2 - *Pteridium esculentum* (Austral bracken fern) can be controlled by herbicides, but several applications may be needed.

INNOVATION AND ROBOTICS IN FORESTRY WEED MANAGEMENT

Bruce A. Auld[1]

ABSTRACT

Traditional and established methods of weed management are outlined, from hand-weeding, to the use of herbicides and biological control. Recent new developments in detection and control methods are introduced, including robotics, microwaves and lasers. Potential roles for the various techniques and management options for forest restoration are then discussed. Robotics could play an important role in accurately detecting and controlling weeds. Low-volume herbicide application, by unmanned aerial vehicles (UAVs) appears particularly suitable. However, integrated weed management, using several methods will probably be required. This should include selection of the most competitive tree species for initial restoration plantings and screening desired tree species for tolerance to herbicides.

***Key words*:** allelopathy, application, detection, drones, herbicides, mulches, resistance, robotics, tolerance, UAVs

INTRODUCTION

Native forests are under threat from continued exploitation with a net reduction in coverage of some one billion hectares worldwide, since the early 1700's. Although restoration is progressing well in some regions (BLASER & GREGSON, 2013), weeds are a major constraint to forest recovery (VASIC et al., 2012). Traditional methods of weed control, in most of the areas requiring forest restoration, are labour-intensive and are consequently becoming increasingly expensive. Moreover, the steep and rugged terrain of many forest restoration sites renders them inaccessible by wheeled vehicles.

In this paper, I review established methods of weed control (Fig. 9.5) and introduce recent developments, including the use of robotics. The potential use of various techniques is then discussed in relation to forestry, particularly forest restoration in northern Thailand.

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ESTABLISHED METHODS OF WEED CONTROL

Chemical

Chemical weed control has been practised since the late 1800's. Herbicides (not 'weed killers', as they do not necessarily discriminate) come in a variety of forms and chemical compositions. They may or may not be selective and the period of their activity varies widely. Since the late 1940's, selective herbicides have been available and there are now many herbicides, usually categorized by their chemical mode of action.

Selective herbicides

Many herbicides are selective in that they affect either grasses (e.g. dalapon) or broad-leaved plants (e.g. 2,4-D). Amongst the latter, some are more effective on woody weeds (e.g. 2,4,5-T). Others have been developed for high selectivity within particular crops, e.g. chlorsulfuron to kill grass weeds (*Lolium* spp.) in wheat (a grass). Some herbicides, with the same active ingredient, may be available in different formulations for different target weeds. For instance, 2,4-D is formulated as an amine salt, a sodium salt or an ester; the latter being more volatile than the former two; the sodium salt can also be applied as a powder.

Non- selective herbicides

Many non-selective herbicides kill a wide range of plant species. Their lengths of residual activity in the soil vary considerably. These range from short-term (e.g. diquat (fast acting) and glyphosate (slower acting)) to longer term (e.g. bromacil). The latter are used in established plantations and industrial situations; those with low water solubility are the safest (e.g. oxyfluorfen).

Application

Herbicides can be applied in a various ways; some as granules and others as liquid sprays. Concentrations of active ingredients, spray volume, droplet size (e.g. CREECH et al., 2015) and adjuvants, such as wetting agents (GASKIN et al., 2013) can all influence treatment efficacy. With large (c. 300 µm diameter) droplets evaporation and drift are reduced, but canopy penetration is also less than with small droplets (c. 100 µm diameter). Halving droplet diameter increases the number of droplets by x 8, for any given volume of spray. Hydraulic sprayers control droplet size by nozzle type and pressure: low pressure and large nozzles produce large droplets and the converse produce small ones. Controlled droplet application (CDA) sprayers control droplet size by rotational speed (Fig. 9.7). Such sprayers are useful for applying low volumes and may be adaptable for use on UAVs or drones (Fig 9.4). Adding dyes to herbicides is useful, to show where herbicide has been applied and consequently avoids spraying the same plants more than once.

Shields around sprayers can protect adjacent plants from herbicides. Liquid formulations may also be applied by hand (e.g. cuts on the stems of large woody weeds) and via wick-wipers (e.g. *www.wickwiper.com*). Some woody species can be controlled by basal bark sprays. Another technique is to use very high concentrations of translocatable herbicide applied in small volumes, sometimes referred as the splatter-gun technique, to control woody weeds such as lantana (*Lantana* spp.). This could be adapted for drone-applied herbicides with limited payload capacity although existing splatter-gun applicators are gas-powered.

Weather conditions can influence herbicide efficacy. A rain-free period of at least a few hours is required for foliar applied sprays; the temperature should be below 28˚C and wind speeds of 2 to 10 km/hr are optimal. Spraying should be avoided when an inversion layer is present (Fig. 9.3), because spray drift may remain concentrated in low clouds and travel long distances.

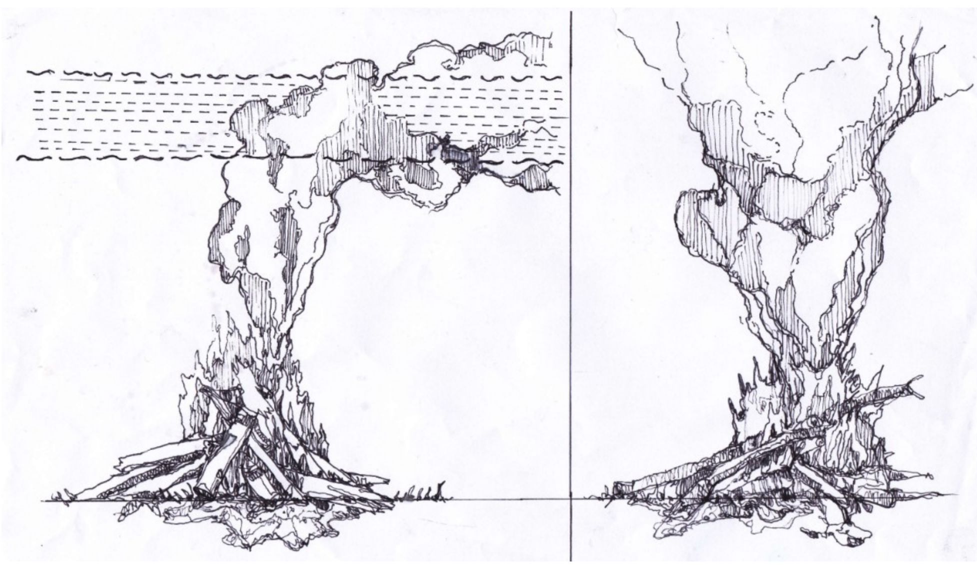

Figure 9.3 – Smoke moving horizontally (left) indicates an inversion layer cf. right

Figure 9.4 – DJI's Agras MG-1S is an eight-rotor craft spanning 1.47 m with a 10-litre liquid capacity. It is priced at US$15,000 (Photo: DJI)

Herbicide resistance

The continued use of one or a few herbicides, with the same chemical mode of action on the same site, will eventually induce herbicide resistance in some species and consequently bring about changes in the composition of the target vegetation. However, herbicide resistance in desired plant species introduces the possibility of their use with that herbicide as a management option. Consequently several commercial, herbicide-resistant, crop cultivars have been bred. Some plant species, although not entirely resistant to some herbicides, may display degrees of natural tolerance to those herbicides; traits that could prove very useful for selective weed control.

Physical

Hand weeding

Although still practised in developing countries and for within-row weeds in some developed agricultures, labour costs generally make hand weeding too expensive for broad-scale agriculture and forestry.

Ploughing

Ploughing, using mechanical or animal power, has the advantage of removing weeds and preparing a seed-bed. In steep terrain (slopes >20˚), the use of wheeled machinery is unsafe and crawler traction machines are required. However, these are unlikely to be employed in many areas because of access problems, damage to useful plants and soil compaction.

Mowing

Mowing or slashing can prevent weeds flowering and seeding and reduce their underground storage reserves. Height and frequency of mowing can be varied to obtain desired results, but mowing alone rarely kills established perennial weeds.

Burning

Broad-scale burning is generally non-selective and although apparently cheap, supplementary costs are involved in preparing fire breaks, monitoring fires and having fire-fighting equipment on standby. The use of fire is very dependent on the fuel load and condition, as well as on weather conditions. Moreover, few vegetation types, such *Eucalyptus* forests in Australia, recover from fire via epicormic buds along their stem.

Use of heat: water / steam / flame

The use of heat is a non-selective method of weed management, suitable for control of annual plants or the suppression of perennials. It requires a portable source of heat (HOYLE et al., 2012). Flame applications may be labour intensive (GHANTOUS et al., 2012) but can utilize all-terrain-vehicle-mounted flamers (KNEZEVIC et al., 2014). Obviously, there will be many situations where burning is too risky to contemplate.

Mulches: plastic, clear and opaque; biodegradable materials

Plastic sheeting has been used for soil solarisation (heating) to control soil borne diseases and also to suppress weed growth (ELMORE, 1991; STAPLETON, 1991). Black 'weed mat' polymer materials, which allow penetration of water but not sunlight, are now widely used in horticultural plantings to surround planted species and protect them from weed interference. They may be held in place by organic materials. Biodegradable organic waste (JOHNSON et al., 2014) produced, for instance, by mowing or slashing weeds, can also be used directly to suppress weeds, retain soil moisture and buffer soil temperature. A biodegradable matting made from linseed straw, has recently been developed in Australia (MIAO et al., 2013). It degrades after a few months. In New Zealand, another biodegradable matting, EcoCover®, is produced from waste paper (http://ecocover).

Flooding

Flooding is used to control weeds in rice and in rice-sugarcane intercropping systems.

Biological

Classical biological control

Classical biological control involves the release of a natural enemy of a specific weed. The biocontrol agent (typically an insect or fungal pathogen) is imported and once established is self-sustaining. A significant aspect of this approach is that the biocontrol agent searches for and finds the target weed. There are many examples of successful biocontrol programs. However, the main limitation is that only one weed species is targeted at a time. Programs are usually aimed at only major weeds, because of the time and resources involved in searching for potential agents before their release and host-range testing. Although biological control agents occasionally attack non-target species, such incidences and their severity are decreasing over time (HINZ et al., 2020).

Inundative biological control

Inundative biocontrol is relatively short-term control achieved by applying high dose rates of an agent (usually fungal spores in a water-based suspension) to a target weed species, creating a short-lived, localised epidemic. The technique, equivalent to having an herbicide specific to one weed species, hence the term bioherbicide (or mycoherbicide), is often used to describe these agents (AULD, HETHERINGTON & SMITH, 2003). Only a small number of these products have been produced, because of several constraints (AULD & MORIN, 1995).

Ecological

Domestic grazing animals

The use of grazing or browsing animals to control weeds is widespread. This technique may require fencing (often solar-powered, portable electrical fencing) to achieve high stocking rates in confined areas, and the provision of water supply points. Goats have been used successfully, particularly for woody weeds and tussock grass control but require careful management. In forestry, such as animals are just as likely to browse on trees as they are to graze on forbs and grasses.

Competitive cultivars

A range of possibilities exist in terms of using crop/tree cultivars with improved competitive ability, planting density and arrangement (a rhomboidal pattern of planting occupies available space best). Interest in cultivars that have allelopathic qualities is increasing.

Cover crops and companion plants

Living mulches, such as annual, leguminous cover-crops may be used to smoother weeds. They can become biological mulches as they senesce. Their sowing times, sowing rates, growth habit and placement, in relation to the desired crop, should always be taken into account. Considerable field experimentation may be required, to establish optimal arrangements.

NEW INNOVATIONS

Detection

Within the last decade, dogs have been trained to detect single plants of newly invading weed species in various environments (e.g. GOODWIN et al., 2010) and, for several years, aerial photography and satellite imagery has enabled delimitation of some widespread species and plant communities. However, the detection of specific weed species, on a scale between these two extremes, has recently been achieved using unmanned robotic vehicles (see below).

Use of air-propelled grits

This is a relatively new innovation that has been used for successful selective control of weeds in crops such as corn, soybeans (FORCELLA, 2009) and vegetable crops (WORTMAN, 2014). Grits are produced from various organic sources including corn cobs, walnut shells and bone meal. Following application, these materials all act as mulches and fertilizers. Application of grits requires specialised high pressure equipment.

Microwaves

Dr Graham Brodie has recently developed a microwave weed controller in Australia (BRODIE, 2017). The prototype device is quite successful at controlling a range of weed species and buried weed seeds, but it is far too bulky to be mounted on UAVs.

Lasers

The use of lasers to damage weeds has been suggested for some time (HOKI, 2000). Recent developments with carbon dioxide laser radiation are encouraging, but they are still at the experimental stage (MARX et al., 2012).

Genetically modified crops with herbicide resistance

New cultivars of certain crops, such as soybeans and cotton, have been developed to be resistant to certain herbicides, including glyphosate by genetic engineering. This greatly simplifies weed management in these crops, but such cultivars may encourage the overuse of herbicides, with consequent negative environmental impacts and the development of new herbicide-resistant populations of weed species. Naturally resistant or tolerant species or varieties could also be employed.

Allelopathic crops

Amongst the various cultivars of some crops, such as barley and rice and their ancestors, allelopathic activity (production of plant compounds that inhibit neighbouring competitive plants) is sometimes found. Selection of such varieties would reduce the need for other forms of weed control (PRATLEY, 2012). Breeding programs and research on allelochemicals and their mode of action may lead to further advances in this field. Some forest tree species, including *Eucalyptus* spp. and *Gmelina* spp. are known to have allelopathic properties, usually via suppression of seed germination.

Robotics

Small unmanned helicopters (Fig. 9.6), such as the Yamaha R-MAX, have been used for several years in Japanese agriculture, especially for sowing and spraying rice. Precision application technology is advancing rapidly in agricultural systems including the development of planting robots (YOUNG et al., 2014).

Detection

Detection and treatment of weeds in crops by light-activated, sensor-controlled, on-ground spraying systems have been progressing (BILLER, 1998; RIAR et al., 2011). Recent advances, using unmanned aerial vehicles (UAVs) flying at low altitudes, have achieved spatial resolutions of 3 pixels per centimetre (TORRES-SANCHEZ et al., 2013; CLEMENTS et al., 2014; GOKTOGAN & SUKKARIEH, 2015). Such a high resolution allows interpretation using spectral response, colour, texture and the 3-D structure of vegetation, enabling discrimination between plant species (HUNG et al., 2012; 2014) cf. other techniques, which use only one or two of these factors.

Application

UAVs can also carry spraying devices for weed control; moreover, the two activities can be linked through GPS recording of the presence of the target species for subsequent treatment.

FOREST RESTORATION IN NORTHERN THAILAND

Roles for established weed control methods

Non-selective herbicides

These herbicides can be used to prepare an area before tree planting. Non-residual herbicides should be used, to avoid possible subsequent damage to growing trees. Herbicides could be applied as strips or in a checker-board fashion (where trees are to be planted) rather than treating an entire area. Some tree species may display degrees of tolerance to some non-selective herbicides, such as glyphosate, depending on application rates. This could be a useful avenue for research with some simple field-based screening experiments on weeds and trees together.

Selective herbicides

Selective herbicides would be most useful, where the main competing weeds were grasses and graminicides such as fluazifop-p-butyl could be used in these situations.

Ploughing / Slashing

These techniques are likely to be limited by costs and difficult terrain, moreover ploughing may expose soil to erosion. Slashing (or mowing) by hand or machine does have the advantages of reducing competition and providing mulch.

Classical biological control

This approach would be suitable where one weed species was dominant, such as crofton weed, *Ageratina adenophora* (Fig 9.1). There are some established biocontrol agents for crofton weed in Australia (AULD, 1969) and elsewhere that are only partially effective. However, a recently introduced host specific-rust fungus is proving highly promising in Australia (MORIN, 2015).

Inundative biological control

As for classical biocontrol, this method typically addresses a single weed species and would only have application where one weed was dominant. There has been considerable research on the fungus *Ascochyta pteris* as a potential bioherbicide for bracken fern (*Pteridium esculentum*) (Webb & Lindow, 1987) (Fig. 9.2), but like many potential bioherbicides creating a formulation to overcome dew requirements of the fungus has been a stumbling block to further development.

There may be a role for allelopathic species and/or products derived from them as broad spectrum bioherbicides, but they would need to be selective *i.e.* not affecting planted trees (see below).

Grazing

The use of grazing animals to reduce weed biomass would depend on their availability, husbandry and the specificity of their grazing behaviour. Access to water and confinement with solar powered electric fencing would probably be required as well as constant surveillance.

Competitive crops / trees

Selection of tree species and varieties for maximum growth rates and other competitive characters should be worthwhile; the influence of provenance may also be important. This work is already in progress as part of the ‘framework species’ method at Forest Restoration Research Unit at Chiang Mai University.

Companion planting

It may be possible to use cover crops such as hairy vetch (*Vicia villosa*) which could smother weeds, provide some allelopathic activity and add nitrogen to the soil (FUJI, 2003). This would require considerable field experimentation to examine sowing rates as well as the interactions with trees and weeds.

Potential roles for new innovations in weed control

Herbicide resistant tree species

The development of native tree species with herbicide resistant genes would require considerable commercial investment and is unlikely to happen in the short-term. However, as mentioned above, some tree species are likely to have tolerance to some herbicides; for example, leguminous trees to glyphosate, and this would be worthy of further investigation.

Allelopathic tree species

Just as allelopathic varieties of crop plants or their ancestors have been found, some degree of allelopathy could exist in forest tree species and to the wider gene pool by selective breeding.

Allelopathic bioherbicides

The use of allelopathic plants as broad spectrum ‘bioherbicides’ is worthy of further investigation. Often with this approach, the bulk of material required to produce an effect makes the idea impractical. However, LAOSINWATTANA et al. (2012) have used granules manufactured from leaves of the native allelopathic tree, *Aglaia odorata*, to achieve selective control of weeds in maize in Ratchaburi Province, Thailand. (If an active chemical ingredient is isolated from such a plant and applied as a spray, it becomes an herbicide, like any other.)

Possible roles for robotics

Detection

Detection capacity is improving rapidly (e.g. HUNG et al., 2014). As suggested above, rather than detecting weeds to spray, detecting forest tree species to avoid spraying may be a promising approach.

Planting

There is scope for planting tree seeds and seedlings together with other materials, such as fertilizer and mulches by drones and this is covered in other papers at this workshop.

Application of herbicides and/or other materials

GPS technology and spray control allows accurate application of herbicides in strips, checker-board fashion or some other programmed arrangement, such as avoiding desired trees. The use of low volume and controlled droplet techniques such as spinning disc sprayers (Fig 9.7) on drones, together with marker dyes, would be particularly useful. Drones could, potentially, also deliver biocontrol agents or carry other weed control devices such as lasers.

CONCLUSIONS

In terms of weed management, robotics can play an important role in weed (or crop) detection, accurate application of herbicides and other materials. Low-volume, controlled-droplet, herbicide applicators, in association with UAVs should be particularly useful. Notwithstanding this, an integrated approach is required, combining several methods to manage weeds and their impacts. Integrated weed management should include selection of the most competitive tree species as framework species. In addition, selecting tree species that are tolerant or resilient to broad-spectrum herbicides is also a promising avenue for research.

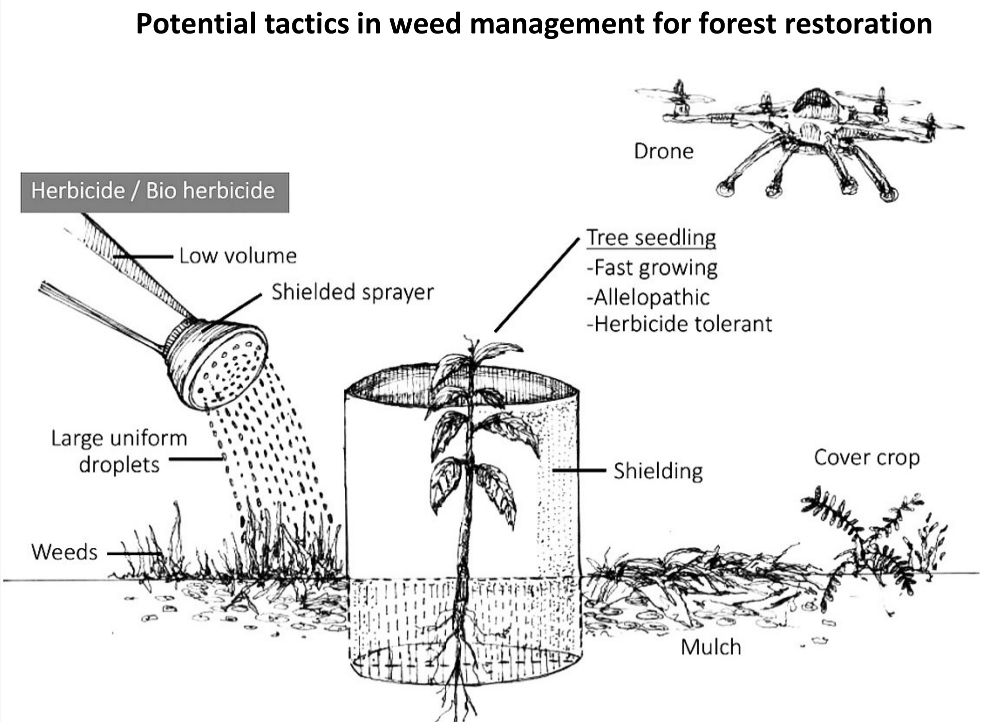

Figure 9.5 - Schematic representation of a variety of approaches to weed management in replanting in forest restoration.

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Figure 9.6 – An auto-piloted mini helicopter, used for weed control

Figure 9.7 - Controlled droplet (spinning disc) nozzles could potentially be used to apply herbicide from on drones. They use low volumes and create large droplets, which would reduce non-target damage.