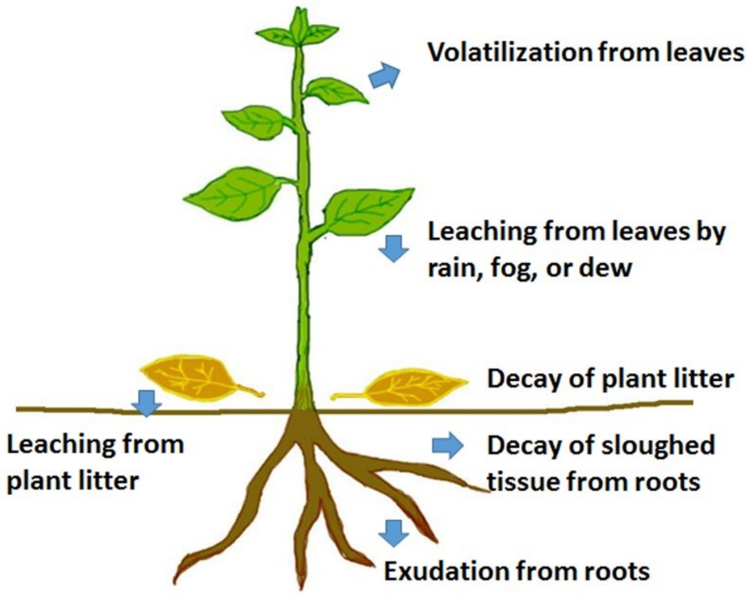

Figure 10.1 - Sources of allelopathic chemicals from plants.

Photo – Stephen Elliott

Figure 10.2 – Allelopathic exclusion of grass by a coppicing *Gmelina arborea* tree, probably due to chemicals leaching from its leaf litter. Note the growth of scandent vines into the grass-free zone by plants rooted outside of it. Could allelopathic chemicals from aggressive pioneer tree species, like *G. arborea*, be used to control weeds during forest restoration? Or would the exclusion of some weed species let others proliferate?

Chapter 10

ALLELOPATHY FOR WEED MANAGEMENT IN FOREST RESTORATION

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ABSTRACT

In forest restoration, weeds compete with tree seedlings for water, nutrients, sunlight and space, as well as act as habitat for pests and diseases. Allelopathy - the inhibition of one plant by another - may allow weeds to be controlled without the environmental hazards associated with synthetic herbicides. Allelopathic compounds, or allelochemicals, are released by different plant parts and processes (e.g. flowers, stems, and root exudates, residue decomposition and volatilization). Plants that exhibit these properties have been identified in both natural and agricultural systems. In this chapter, we discuss the potential uses of allelopathy for weed management in forest restoration. This includes the planting of allelopathic tree species, the incorporation of allelopathic plants or weeds into planting sites, and the use of allelochemicals in auto-weeding for automated forest restoration. Auto-weeding, using allelopathy, could be a more environmentally friendly, cost-effective alternative to synthetic herbicides in forestry systems. However, research is required to identify the source and target species of allelochemicals, evaluate their effectiveness in the field, and determine the optimal timing, rate, and application methods, for their use.

***Key words*:** allelopathy, allelochemicals, auto-weeding, invasive weed

ALLELOPATHY FOR WEED MANAGEMENT

In forest systems, herbaceous weeds compete with tree seedlings for water, nutrients, sunlight, and growing space. Weeds also provide habitat for pests and disease organisms (ZIMDAHL, 2013). Foresters commonly employ synthetic chemical herbicides to control weeds. However, synthetic herbicides are costly and may be hazardous when used improperly. Synthetic herbicides may cause additional unforeseen health and environmental consequences, if the chemicals drift to non-target

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organisms and persist in the environment (ZIMDAHL, 2013). These risks impede their use in sustainable forest restoration.

"Natural" herbicides, from plant secondary metabolites, represent a promising alternative, although they may have some of the same shortcomings. Secondary metabolites are organic compounds that are produced at the end of biosynthetic pathways. They are therefore not required for plant growth and development. Instead, they aid in plant survivability and fecundity (GUTZEIT & LUDWIG-MÜLLER, 2014). For example, they may attract pollinators or seed dispersing animals, repel herbivores or pathogens or increase tolerance of abiotic stress. Plant secondary metabolites are often multifunctional, providing in an array of biological activities, some of which have been exploited for human use (MACÍAS et al., 2007). Secondary metabolites with allelopathic effects (i.e. allelochemicals) in particular have considerable potential as potential herbicides to control weeds in sustainable forest restoration.

Allelopathy is "the chemical inhibition of one plant by another" (RICE, 1984). Allelochemicals are recognized tools for weed management in both agriculture and forests (CUMMINGS et al. 2012; MACÍAS et al., 2007). Unlike some synthetic herbicides, allelochemicals often have short half-lives and decompose into innocuous organic compounds (DUKE et al., 2000). Allelopathic plants release allelochemicals into the environment by leaching, root exudation and volatilization (Fig.10.1). MACÍAS et al. (2007) provide four conditions to identify allelopathic events. They include i) a plant distribution that cannot be explained by physical or biotic factors, ii) the proximity of allelopathic plants that synthesize and release bioactive chemicals, iii) the presence of appropriate concentrations of allelochemicals in the soil to reach the target and finally, iv) evidence of either detrimental or beneficial effects caused by allelochemical uptake in target plants. In forest restoration, this approach to identifying allelopathic plants can be applied to selecting allelopathic tree species for planting and for determining which allelochemicals might be appropriate for incorporation at the planting site.

Identifying tree species with allelopathic properties

Many weed species are unable to thrive beneath the shade of over-story forest trees. In some cases, however, this inhibition is in part the result of allelopathy by trees, rather than simple competition for light in the understory (BHATT et al., 2010) Exotic weed species may be particularly susceptible to allelopathy from native trees (CUMMINGS et al., 2012). This suggests that native tree species could be used in forest restoration to suppress troublesome exotic weeds.

Certain plant families or genera have been associated with high concentrations or high diversity of secondary metabolites with potential allelopathic effects (SINGH et al., 2003; WINK, 2003). Tree species in the Fabaceae family are associated with nitrogenous defensive compounds (WINK, 2003). For example, CUMMINGS et al., (2012) found that leaf litter from native leguminous tree species in Central America (*Inga punctate*, *Gliricidia septium*, and *Diphysa americana*) had a greater inhibitory effect on the invasive Asian grass, *Saccharum spontaneum*, than non-leguminous trees did. Furthermore, several studies have demonstrated the ability of allelopathic native trees to protect themselves against exotic weeds. HOU et al., (2012) reported that, in a pot experiment in China, seedling growth of the invasive South American weed, *Mikania micrantha*, was inhibited by the application of leaf litter extract from four native trees, *Schima superba*, *Castanopsis chinensis*, *Castanopsis fissa*, and *Cryptocarya chinensis*.

In order to determine the allelopathic strategy of trees, researchers must test extracts from their leaves, leaf litter, flowers and roots on weed seed germination and seedling growth, and monitor the response of weed seeds or seedlings to soil beneath the trees. CUMMINGS et al., (2012) reviewed published investigations of trees suspected of having allelopathic properties. Not all trees, however, demonstrate allelopathy. For example, FINE et al., (2006) found that fast-growing pioneer trees tend not to produce allelochemicals. This may be the result of a trade-off between energetic investment in rapid growth and chemical defense. This suggests that tree species traits may be correlated with allelopathic activity. If we knew which traits are most strongly predictive of allelopathy, we may be able to more rapidly identify allelopathic native tree species for weed control in forest restoration.

Incorporating plant residues and allelochemicals into the soil

In addition to identifying trees with allelopathic potential, research on allelopathy for forest restoration could include techniques for the use of plant residues or extracts at planting sites. Allelopathic plant residues can be surface-applied, as mulch, or incorporated into soil for weed suppression. Other potential weed-control agents include allelochemical extracts from plant parts, residues, leaf litter, or soil from around allelopathic plants. These too can be incorporated directly into soil or directly applied to target species. Although the allelopathic effects of weeds have most often been viewed as a hindrance to forest regeneration, it may be possible to exploit their allelopathic properties in order to aid it. For example, some invasive, highland, weed, species such as *Ageratina adenophora*, *Chromolaena odorata* and *Bidens pilosa* have allelopathic effects on seed germination and growth

(Table 10.1). They may be useful sources of allelochemical extracts or soil incorporates to control other weed species.

Table 10.1 - Examples of invasive weed species and their allelopathic effects.

Weed species	Target species	Allelopathic effect	Allelo-chemicals	Citation
Ageratina adenophora (Spreng.) R.M. King & H. Rob.	*Arabidopsis thaliana*	Effect of root extract on germination of herb	Terpenes	ZHAO et al., 2009
Ageratina adenophora (Spreng.) R.M. King & H. Rob.	*Arabidopsis thaliana*	Effect of root extract on germination and growth of herb	Phenols	ZHOU et al., 2013
Bidens pilosa L.	*Raphanus sativus* *Echinochloa crus-galli* *Corticum rolfsii* *Fusarium solani* *Fusarium oxysporum*	Effect of leaf, stem, and root extracts on germination and growth of crops, weeds, and fungi	Phenols	DEBA et al., 2007
Centaurea diffusa Lam.	*Festuca ovina* *Koeleria laerssenii* *Agropyron cristatum*	Effect of root exudate on growth of native grasses	-	CALLAWAY & ASCHEHOUG, 2000
Chromolaena odorata (L.) R.M. King & H. Rob. & *Lantana camara* L.	*Capsicum frutescens* *Brassica chinensis* *Cucumis sativus* *Brassica juncea* *Amaranthus viridis*	Effect of leaf litter extract and soil, collected from invaded area on emergence and growth of crops and weeds	-	SAHID & JOHN, 1993
Rottboellia cochinchinensis (Lour.) Clayton	*Bidens pilosa* *Echinochloa crus-galli* *Lactuca sativa*	Effect of soil, collected from invaded area, on germination and growth	*Trans-p-*coumaric acid	MEKSAWAT & PORNPROM, 2010

Identifying sources of allelochemicals and synthesizing

The molecular composition and mode of action of some targeted allelo-chemicals may suggest novel strategies for herbicide action and thus spur the development of more effective herbicides (MACÍAS et al., 2007). Examples where this has been successful include the development of the commercial 'natural' herbicide product, NatureCur®, from black walnut (*Juglans nigra*) extract (SHRESTHA, 2009) and the commercial herbicide, glufosinate, based on the chemical structure of the natural product, bialaphos (MACÍAS et al., 2007). For a more complete review of prominent, known allelopathic compounds and their mechanisms of action, please see INDERJIT & DUKE (2003).

Advantages and limitations of allelopathy

The allelopathic potential of plants or their sensitivity to allelochemicals from other plants depends largely on the amount, concentration and form of the allelochemicals, as well as the timing of their introduction (ZIMDAHL, 2013). Allelochemicals may also have differential effects, depending on species. For example, HSU & KAO (2009) found that aqueous extracts of the leaves, stems, and roots of the introduced species, *Bidens pilosa*, inhibited germination and growth of the same species and a sympatric species, *B. bipinnata,* but not a second sympatric species, *Ageratum conyzoides*. This suggests that some allelochemicals have the potential to target specific weeds. Ideally, this could be used in forest restoration to target certain noxious weed species, while leaving desirable species, such as planted trees, unaffected. On the other hand, it may be difficult to predict the long-term effects of allelopathic interactions on non-target species, particularly when employing long-lived allelopathic trees in restoration plantings. Some trees, such as *Gmelina arborea* (Fig 10.2) and *Eucalyptus*, are known to have such potent allelopathic properties that they decrease plant species diversity within their proximity (CHU et al., 2014).

When used directly as bioherbicides, allelochemicals may have significant advantages over traditional synthetic herbicides. These 'natural' herbicides may pose fewer environmental risks than synthetic herbicides do, if they target only certain species (NOLLET & RATHORE, 2015). Furthermore, rapidly decomposing allelochemicals reduce the risk of residual contamination and secondary transport from the planting site (DUKE et al., 2000). They may also decrease the incidence of herbicide-resistance in weed populations or provide alternative methods for control, where herbicide-resistance prevents use of conventional herbicides (ZIMDAHL, 2013). There are, however, some potentially significant limitations to using allelochemicals as herbicides and in herbicide development. The short environmental half-lives of many naturally-occurring allelochemicals may preclude their use as effective herbicides, since some phytotoxic persistence is often desirable in weed management. Moreover, obtaining sufficient quantities of extracts for effective weed control may be impractical (DUKE et al., 2000).

Given these limitations, it may be possible to use the molecular composition and mode of action of some targeted allelochemicals instead, to suggest novel strategies for herbicide action. This may spur the development of more effective herbicides that can be synthesized for application in forest restoration (MACÍAS et al., 2007; ZIMDAHL, 2013). However, the process of identifying, isolating, and determining the structure of the allelopathic compounds may be prohibitively expensive. Even after this process has been undertaken, it may be too costly or impractical to synthesize the complex phytotoxic molecules of naturally occurring allelochemicals in quantities sufficient for operational use (DUKE et al., 2000). Moreover, to comply with regulations, these potential products would still have to be tested for efficacy and toxicity.

AUTO-WEEDING FOR AUTOMATED FOREST RESTORATION

Auto-weeding refers to the automated application of herbicides to forest restoration sites for the purpose of weed control (Fig. 10.3). In order to apply allelopathy to auto-weeding, however, we must first identify the particular allelochemicals that target undesirable weed species and determine appropriate concentrations, application times, and application methods, as well as conduct a cost-benefit analysis. Furthermore, additional research is needed to determine whether the allelopathic effects are broad-spectrum or species-specific. We also need to identify biotic and abiotic interactions that may alter the production and effectiveness of the allelochemicals. For example, the concentration and production of allelochemicals by plants may be affected by nutrient deficiency (VARKITZI et al., 2010), stress (TONGMA et al., 2001) and soil microorganisms (BOREK et al., 1994). We should then characterize the conversion process and identify the degradation products of the allelochemicals in the environment (MACÍAS et al., 2007). Moreover, beyond lab or pot experiments, the development of practical application and formulation techniques are key to the effective use of allelopathic chemicals for forest restoration.

One potential use for auto-weeding is pre-emergent weed control on forest restoration sites. These sites often possess a high diversity of weed seeds in the soil seed bank. These weeds may re-establish rapidly after land clearing and compete with planted or naturally regenerating trees. Application of allelochemicals could possibly be followed by a rest period, to allow biochemical processes such as chemical fractionation that may or may not require moisture to break down allelopathic compounds. Consequently, the timing of the initial application may be critical, because incorporation and degradation of the compounds may require interactions with seasonal abiotic processes, such as rain and biotic processes, such as soil microorganism activity (GIMSING & KIRKEGAARD, 2008). Aerial seeding would then follow, though reapplication of phytotoxic extracts may be need after seedling establishment, to control newly emerged weed seedlings.

INTEGRATED WEED MANAGEMENT FOR AUTOMATED FOREST RESTORATION

Allelopathy represents just one of several possible weed management strategies. Mechanical, cultural, and biological techniques also hold great promise for managing weeds in forest restoration. Rather than focusing solely on the development of biochemical tools, our goal should be to maximize the effectiveness of weed control, by combining allelopathy with other techniques into an integrated management system (NOLLET & RATHORE, 2015).

Allelopathy is a promising tool for future weed management strategies that may reduce the persistence of exotic weeds with fewer side-effects for people, property, and the environment. This contribution, however, is highly dependent upon the success of research into identifying and characterizing allelopathic species and chemicals, and the development of practical techniques for applying allelopathy to automated forest restoration.

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Figure 10.3 - Testing of auto-spraying for weed management in an agroforestry system