Scoping study of sustainable weed management in tea tree oil plantations
Review of Literature

by Michael Coleman, Paul Kristiansen, Christine Fyfe and Brian Sindel
November 2020
Scoping study of sustainable weed management in tea tree oil plantations

Review of Literature

by Michael Coleman, Paul Kristiansen, Christine Fyfe and Brian Sindel

November 2020

AgriFutures Australia Publication No. 20-129
AgriFutures Australia Project No. PRJ-011789
7.6.4. Perennial cover crops ................................................................. 23
7.6.5. Site management and crop competitiveness .......................... 25
7.7. Integrated Weed Management .................................................. 25

8. Knowledge and research gaps ..................................................... 27

8.1. Gaps related to the impact of weeds ........................................ 27
8.2. Gaps related to weed management practices ......................... 27
  8.2.1. Alternative herbicides? .................................................... 27
  8.2.2. Herbicide resistance ....................................................... 29
  8.2.3. Stale and false seed beds ............................................... 30
  8.2.4. Killed mulches and strip tillage during crop establishment ... 30
  8.2.5. Synthetic mulch films during crop establishment ............... 31
  8.2.6. Biodegradable mulch films during crop establishment ....... 31
  8.2.7. Crop row orientation ...................................................... 32
  8.2.8. Weed identification, scouting and mapping ....................... 32
  8.2.9. Thermal weed control in establishing and established plantations ... 33
  8.2.10. Robotics and automation in establishing and established plantations ... 34

9. Extension needs ............................................................................ 34

10. References .................................................................................. 36
Tables

Table 3.1  Weed species identified in Australian tea tree plantations in previous research......... 6
Table 4.1  Economic impact of weed interference on tea tree crop yield under two planting
density scenarios................................................................................................................................... 10
Table 5.1  Herbicide availability within Australian tea tree crops, including timing, 2020 ........ 15
Table 5.2  Herbicides recommended by McMillan and Cook (1994), and their current registration
status for tea tree................................................................................................................................... 28
1. Executive Summary

Tea tree (*Melaleuca alternifolia*) is grown commercially in Australia as an intensive row crop planted at sufficiently high densities to maximise per-hectare productivity.

In 2016, approximately 4,000 hectares of plantation tea tree in Australia with an estimated 140 tea tree oil (TTO) producers in 2020, most being members of the industry peak body, Australian Tea Tree Industry Association (ATTIA). Production areas per farm ranged from five to over 700 hectares. In 2018-19, the export value of Australia’s tea tree production was estimated at $34.5 million.

Most Australian tea tree plantations are located in the Northern Rivers and Mid-North Coast regions of New South Wales (NSW) with a smaller but significant cluster of plantations in the Atherton Tablelands region of Queensland (QLD).

1.1. Important weeds in the industry

Predominant weeds found in Australian TTO plantations include a mixture of broadleaf, grass and sedge weeds, mainly annual but some perennial species also. Annual weeds are most likely to pose problems for TTO producers in the period following harvest or during cultivation activities associated with establishment of a new crop. Both activities create bare ground for annual weeds to germinate. Perennial weeds are often favoured by production systems featuring minimal soil disturbance, a key characteristic of tea tree plantations once established.

Herbicide-resistant grasses have been anecdotally noted within industry. Information on the extent of resistance is not available in the literature however some broadleaf weeds are noted to be less than fully controlled by certain herbicides on farms, while others are noted as resistant to certain herbicides in other cropping industries. This information suggests considerable potential for herbicide resistance developing within tea tree plantations, if not already present.

1.2. Impact of weeds on tea tree

Weed control is considered an important aspect of crop management in tea tree. They are considered a major limitation to tea tree production, and major cause of poor crop establishment or crop failure.

Most significant competition from weeds occurs during the first two months after planting within tea tree crops. Yield losses of up to 97% can occur where high weed densities are present during this period following crop establishment.

Impacts of weeds on TTO production can include:

- Competition for light, moisture and nutrients.
- Potential allelopathic effect that may hinder the growth of recently planted tea tree.
- Potential for weed biomass collected during harvest to dilute or taint the purity of tea tree oil.

These impacts can have significant repercussions for crop yield and profitability, and crop and farm management.

1.3. Current weed control approaches

Methods used to control weeds in tea tree plantations include:

- Herbicides
- Cultivation
- Mowing or slashing,
• Grazing
• Green manure/cover crops
• Mulches
• Burning.

Weed control practices which are common to annual cropping systems, such as fallow cultivation or herbicide application, and crop rotation, are not available in perennial tea tree crops. Consequently, tea tree weed management is more difficult than in these annual systems. An effective weed management strategy in tea tree plantations will integrate a range of practices, accounting for time of year, weed species present and crop life stage.

Weed control during *crop establishment* involves preparing the ground for initial planting of the tea tree crop by reducing weed seed bank and minimising the number of weeds present in the soil. In perennial crops such as tea tree, this is especially important for perennial weeds, which can be more difficult to manage once the crop has been established. Site preparation weed management should start at least 12 months before the crop is planted. Options include non-selective herbicides, repeat cultivation passes, and pre-emergent residual herbicides used at planting. Seedling tea tree crops are particularly susceptible to weed competition requiring a weed-free period of approximately 12 weeks after planting to ensure successful establishment.

After the initial harvest, a long-term annual cycle of plant shoot re-growth and harvest takes place. Within the *annual regrowth cycle*, the critical period of weed control is the first few weeks after harvest. This opportunity is used to control existing and new weed cohorts, before the crop canopy closes again. Weed control methods include:

• Post-harvest non-selective herbicide.
• Selective herbicide within the regrowing crop.
• Mulching, effective weed suppression in the inter-row space.
• Shallow inter-row cultivation and grazing.

The goals are to minimise the impact of weeds on re-growth yield and weed contamination of the next harvest.

Herbicides are considered the most effective and affordable weed management technique in tea tree plantations. Pre-emergent residual herbicides are applied to the soil surface to control germinating weeds prior to planting of tea tree seedlings (pre-sowing pre-emergence) or immediately after planting (post-sowing pre-emergence). Within an established tea tree crop, post-emergent herbicides may be used to control weeds between crop rows (inter-row space), directed away from tea tree plants using shielded spray equipment to avoid crop damage. Some post-emergent selective herbicides are available for over the top application to control a specific range of weed species. Non-selective herbicides may be used over the top of the crop following harvest and before coppicing (re-growth), where few if any crop leaves are available to translocate the herbicide.

Pre-plant cultivation is used during bed formation prior to crop planting and is considered effective in managing weeds in plantations before planting and during seedling bed preparation. It may also be used between crop rows (inter-row cultivation), although this practice appears to be primarily limited to recently established plantations, where it may be used before the first harvest and where the crop roots have not had a chance to spread significantly into the inter-row space. Inter-row cultivation within a recently planted crop aims to produce relatively shallow soil disturbance to kill recently germinated weeds, without damaging the tea tree crop roots that have not yet spread into the inter-row space. It is limited by a range of disadvantages which appears to restrict its use amongst tea tree producers.

Mowing is used to reduce the competitiveness of weeds with the crop, by cutting weeds in the inter-row space near ground level. It can also assist in managing and eventually reducing the weed seed bank, by limiting the number of weed seed produced. However, mowing is ineffective for killing most weeds
present, as the growing point of weeds will generally be below the cutting height. It is also considered to be relatively poor value for money with regards to weed control.

Due to its high cost, hand weeding is only recommended in tea tree and other crops for ‘spot-weeding’ (for example, of new weed outbreaks, particularly impactful individual weeds, or in order to remove weeds with seed heads from the paddock to reduce the weed seed bank).

Organic mulches (such as tea tree litter) can deliver excellent weed control within tea tree rows and in the inter-row space and provide a range of other crop advantages. However, the mulch layer must be sufficiently thick or suppressive so that weed germination and growth minimised through light suppression. More mature perennial weeds are considered particularly effective at growing through organic mulch layers due to their extensive root systems, although mulch achieves good control of recently germinated weeds. To maximise its effectiveness, mulch should be applied to a paddock that has already been well managed for established weeds.

Effective farm hygiene restricts the spread of weed seeds and reproductive plant parts (propagules) from one location to another. This can include weed spread from farm to farm, as well as weed spread within the farm. Relevant activities are commonly referred to in tea tree production and other cropping systems as preventive weed control.

Grazing may be effective within more mature plantations, resulting in minimal crop damage given that tea tree is not palatable to livestock. Its short-term benefits can be expected to be similar to mowing, particularly if stocking rates/grazing intensity are high, however livestock are considered to have some benefit in controlling the type of woody perennial weed species favoured by tea tree production systems, particularly in their seedling stage.

Decisions taken in selecting, establishing and maintaining a plantation site and the subsequent crop, can have implications for tea tree’s competitiveness against weeds. A range of considerations are available to maximise crop competitiveness against weeds, including suitable site drainage and layout, selection of ideal harvest time, and facilitating maximised tree growth.

Integrated Weed Management involves combining all appropriate weed control options in a coordinated and flexible way to minimise the impact of weeds. Relying on one or two tried and true methods alone (such as herbicides) is less likely to succeed in the longer term. Integrating a range of approaches and timing them appropriately so that they support each other will reduce selection pressure and make it less likely that particular weed species will come to dominate the plantation.

1.4. Knowledge and research gaps

This literature review suggests a lack of information in a range of areas regarding the impact of weeds within tea tree plantations in Australia. These include: the farm-level economic impact of weeds on TTO production; whether weeds have an allelopathic effect on tea tree; whether any common weeds host detrimental insects or diseases; whether weed biomass impacts negatively on TTO quality.

The literature review also identified possible opportunities to expand the range of weed management options and opportunities available in tea tree production, many of which are used effectively in other cropping systems. These are summarised in the table below.

<table>
<thead>
<tr>
<th>Weed management opportunity</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternative herbicides?</td>
<td>Flumioxazin is likely to become available to tea tree producers soon as a post-harvest and post-emergent product. Further industry consultation may confirm the suitability and current trial status of quizalofop-p-ethyl, sethoxydim and a haloxyfop/clethodim tank mix, and potentially identify other suitable herbicides for future screening research.</td>
</tr>
<tr>
<td>Weed management opportunity</td>
<td>Summary</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>Herbicide resistance</td>
<td>What is the extent of herbicide resistance in the tea tree industry, particularly in relationship to the most significant weed species and registered/permitted herbicides? How can resistant weed populations be managed to mitigate this risk to the industry?</td>
</tr>
<tr>
<td>Stale and false seed beds</td>
<td>Stale and false seed beds are likely to help TTO producers to reduce the weed seed bank during crop establishment, but their potential usefulness within an established crop is likely to require field evaluation.</td>
</tr>
<tr>
<td>Killed mulches and strip tillage during crop establishment</td>
<td>Establishing a new tea tree crop within a killed mulch may help to retain soil moisture and structure in the early days of the crop and provide some competition for weeds. It would be possible to use herbicides over the top of the killed mulch to control weeds, however the benefits of the killed mulch layer would only be short-term as the cover biomass breaks down. Field trials may identify the potential benefits of this technique for weed and soil management. Strip tillage is unlikely to be relevant to tea tree plantations, given: its potential to reduce crop yield through competition; ongoing management requirements of the inter-row green strip being identical to that of a perennial cover crop; and because its ongoing presence would preclude options such as shielded inter-row or selective herbicide application which may damage the cover crop layer.</td>
</tr>
<tr>
<td>Synthetic mulch films during crop establishment</td>
<td>Synthetic mulch films are unlikely to be suited to tea tree plantations.</td>
</tr>
<tr>
<td>Biodegradable mulch films during crop establishment</td>
<td>Biodegradable mulch films may offer TTO producers an extra tool in suppressing weeds from plantation establishment through to first harvest. However, their performance and cost-effectiveness vs ‘standard’ crop establishment practices needs to be evaluated in the field.</td>
</tr>
<tr>
<td>Crop row orientation</td>
<td>East-west crop orientation shows promising signs for improving crop competitiveness with weeds in other crops. It may offer similar assistance in tea tree, though field trials would be required to explore crop-weed and crop-crop competition factors, comparative crop yields, and comparative weed burdens. Such orientation would also need to suit the physical characteristics of each site.</td>
</tr>
<tr>
<td>Weed identification, scouting and mapping</td>
<td>Understanding the ecology, behaviour and locations of important weeds within tea tree plantations may assist TTO producers to ensure control activity is tailored appropriately to these species. Information on behaviour and effective management of important weeds may be required to allow targeted control.</td>
</tr>
<tr>
<td>Thermal weed control in establishing and established plantations</td>
<td>Saturated steam weeding is already showing promising results in Australian TTO production and may offer an alternative to herbicides for safe control of recently germinated weeds in particular in tea tree plantations. Possible limitations and relevance to control of mature and perennial weeds require further trial. Flame weeding is unlikely to be suitable.</td>
</tr>
<tr>
<td>Robotics and automation in establishing and established plantations</td>
<td>Robotic weeding systems is a relatively new technology which continues to advance rapidly. Robotic weed management has considerable potential in TTO production, though field trials and economic evaluation should be undertaken, particularly given the relatively small scale of many tea tree operations.</td>
</tr>
<tr>
<td>Weed management extension</td>
<td>Other cropping industries in Australia have access to detailed (IWM) guidelines in written form. Alternatively, TTO producers may benefit from detailed management guides specific to important ‘priority weeds’, drawing on general ecology and management information sources, and written in a form relevant to TTO production.</td>
</tr>
</tbody>
</table>
2. Objectives

This research will contribute to Tea Tree Oil RD&E Objective 1, Improving supply and Objective 3, Extension, sustainability and human capital (AgriFutures Australia 2018).

This review of the literature (Project Task 1) contributes to a range of objectives of the scoping study, by exploring the impact of weeds and their management activities, limitations in current management approaches, and possible ways to address these limitations as identified in previous research.

Lessons from similar relevant perennial cropping systems are summarised from the literature, particularly with regard to weed management techniques which may be relevant to tea tree plantations (Chapter 8).

The review of literature also contributes to identifying and prioritising topics of consultation with producers, agronomists and other experts, and chemical industry, which form Project Tasks 2 and 3.
3. Methodology

Weed impact and control issues, and gaps in knowledge, were explored through a review of Australian and international literature.

Literature searches were conducted using the University of New England’s library catalogue (printed publications and online documents available through several academic literature databases), the Google Scholar and Google search engines, and amongst the literature collection of the School of Environmental and Rural Science, University of New England.

The initial scope of the literature search was Australian academic literature, although the lack of relevant articles led us to expand our search to include extension publications and industry reports. The ATTIA web site was searched for relevant references, and these acquired from ATTIA where an electronic copy was available.

Other relevant web sites were also searched, including those of the Council of Australian Weed Societies (where a library of Australian Weeds Conference papers is freely available), research organisations, and the Australian Bureau of Statistics. Herbicide labels were obtained from relevant manufacturers to compile herbicide registration lists.

Some unpublished reports and data were acquired from their authors, while experts were consulted on specific points where literature could not be found or was insufficient.

International literature on similar perennial and/or narrow row cropping systems was also sourced for comparative purposes, or to fill gaps in the review where *M. alternifolia* literature could not be found. Searches were carried out for *Melaleuca* production outside Australia, but few resources were identified. Examples of similar cropping systems where relevant literature was obtained included blueberry, forestry, lavender, macadamias, orchards, raspberries, sugarcane, and vineyards. ‘Weed management in narrow row crops’ and ‘weed management in perennial row crops’ were also search terms used to identify approaches with potential relevance to tea tree plantation management, and used in combination with other relevant search terms such as ‘mulch’, ‘inter-row cultivation’, ‘mowing’ etc. Remaining gaps in knowledge will be filled through Tasks 2 and 3 (consultation with producers, experts and the chemical industry).

Despite this extensive search, the authors acknowledge that the literature review is relatively thin in some areas, and particularly reliant on several key references. This reflects a lack of information on some aspects of weed impact and control in tea tree plantations, particularly more recent studies and/or extension documents. Tea tree production is relatively unique in many ways, including weed management requirements. This emphasises the need to develop weed management priorities for tea tree plantations and use these priorities to guide further research in improved weed management to benefit Australia’s TTO producers.
4. Tea tree oil production in Australia

4.1. Key characteristics of the production system

Tea tree (*Melaleuca alternifolia*) is grown commercially in Australia as an intensive row crop, planted at sufficiently high densities to maximise per-hectare productivity.

Crop seedlings are grown in nurseries until they reach three to five months of age, and are then planted in the field (AgriFutures Australia n.d.). Before establishing a new plantation, preparatory weed control, levelling and drainage establishment, and breaking up compacted soil layers may be required to maximise the likelihood of successful plantation establishment. A level site with good drainage is also advantageous in making machinery operations possible relatively quickly after flooding or heavy rainfall. Irrigation is usually necessary to support initial plantation establishment (Sutton et al. 1997).

Trees are usually between 1 and 2 metres high at the time of harvest. Initial harvest usually occurs 1-3 years after the crop has been transplanted, depending on climate and crop growth rate. Harvest takes place every nine to eighteen months depending on region and climate and occurs once the crop canopy is fully developed and maximum leaf yield has been reached on the trees. The harvesting process involves cutting the plant to a height of approximately 100mm above ground level, for the leaves to be distilled to produce tea tree oil. This process is known as ‘coppicing’, and results in vigorous re-growth but also opens up the crop canopy and creates significant bare ground that may last for several months following harvest. Harvested materials are mulched into smaller fragments, and taken to a distillery for TTO extraction (Sutton et al. 1997, Colton & Murtagh 1999, Virtue et al. 2000, Carson et al. 2005).

4.2. Value, volume, area of production

The Australian TTO industry was originally based on harvesting from naturally occurring specimens typically found in damp, sub-tropical conditions of the NSW north coast, following reports of its economic potential and range of application in the 1920s (Carson et al. 2005). Since the 1980s, the industry has evolved into commercial plantations, with more intensive production and new cultivars (courtesy of a tea tree breeding program that has been operational for more than 25 years) resulting in significantly increased yield per hectare (Colton & Murtagh 1990, Colton & Murtagh 1999, AgriFutures Australia 2018, AgriFutures Australia n.d.).

The most recent data available at the time of writing suggested that just over 1,000 metric tonnes of TTO had been produced in Australia (for the 2018-19 year), of which approximately 20 metric tonnes came from organic producers (Larkman 2019). In 2009, production was less than half this amount (427 metric tonnes), and had grown steadily each year in between, but was projected for an unprecedented significant drop in 2019-20, due to ongoing drought in key production zones (ATTIA 2019). Australia is the largest producer of TTO globally (AgriFutures Australia 2018).

In 2016, there were approximately 4,000 hectares of plantation tea tree in Australia, and today there are an estimated 140 TTO producers, of which most are members of the industry peak body, the Australian Tea Tree industry Association (ATTIA). Production areas per farm ranged from five to over 700 hectares. In 2018-19, the export value of Australia’s tea tree production was estimated at $34.5 million. Australian production has been estimated to be approximately half worldwide *M. alternifolia* essential oil production, comprising several countries with China a major contributor (Brophy et al. 2013, AgriFutures Australia 2018, ATTIA 2019, Larkman 2019).
4.3. Domestic and export markets

Over 80% of tea tree oil produced in 2018-19 was exported (major markets are located in Europe and North America), while the remaining demand came from local markets (ATTIA 2019). TTO is used in healthcare, cosmetics, pharmaceuticals, veterinary and aromatherapy products, and also sold as a 100% pure product (AgriFutures Australia 2018).

Market competition for Australian TTO comes mainly from China, however this product is usually of a lower quality and adulterated with waste by-products. Other competitors may be found elsewhere in south-east Asia, and southern Africa, with some competition coming from extracts of *M. cajuputi* and *M. quinquenervia* (Brophy et al. 2013, AgriFutures Australia 2018).

4.4. Industry location, climate and soil requirements

Most Australian tea tree plantations are located in the Northern Rivers and Mid-North Coast regions of New South Wales (NSW), with a smaller but still significant cluster of plantations in the Atherton Tablelands region of Queensland (QLD) (AgriFutures Australia 2018).

*M. alternifolia* is a hardy plant and is adaptable to a variety of climate circumstances and soil types. Naturally occurring populations may be found growing in humid sub-tropical regions of northern NSW, but also as far afield as Stanthorpe in south-east Queensland (Brophy et al. 2013). Achieving consistent high yields from tea tree plantations requires relatively specific climate and soil conditions, as well as management of natural hazards, which mimic or approximate its natural environment. This information has been summarised from Virtue (1997) Colton and Murtagh (1999) and ATTIA (n.d.).

- **Temperature.** Research has found tea tree to be very tolerant of high temperatures, and generally preferring warmer temperature. Tea tree and has been grown very successfully in trials where temperature is as high as 35°C at daytime and 30°C at night. Annual growth rates are approximately 50% higher in north QLD, with its warmer year-round temperatures, than in northern NSW. In the Northern Rivers, plantations lay near-dormant for 3-4 months during the winter and begin to grow once the mean temperature exceeds 17°C. Oil concentration within plant leaves also appears higher in warmer temperatures. Frost can severely damage young tea tree plants.
- **Rainfall.** Tea tree plants can survive in drought and dry conditions, however high levels of rainfall such as those experienced in northern NSW (1,000-1,500mm annually) are ideal for maximum growth and productivity. Plantation areas in NSW usually experience relatively dry early spring conditions, followed by good rainfall from late summer through to autumn. Plantations growing in the Atherton Tablelands, QLD, also succeed with lower and more summer-dominant annual rainfall.
- **Humidity.** Higher levels of humidity have been associated in glasshouse trials with greater oil concentration in crop leaves.
- **Soil type.** Naturally occurring tea tree plants are generally found in swampy or coastal flood plain regions, on alluvial soils. It will grow on a variety of soil types; however plantation tea tree performs best on well-draining deep sandy loams of high fertility, which are capable of retaining moisture during the dry season to maintain growth. Lighter, fast-draining sandy soils can still be used to grow plantation tea tree, however this requires access to significant irrigation water to maintain the plants during dry weather, or a permanent water table. Heavy clay soils which impede draining after heavy rain or flooding can restrict tea tree growth. These can make it difficult to operate in the plantation after heavy rainfall or flooding, and potentially result in soil compaction. Acid or neutral soils are preferred (pH 4.5-5.5 preferred); tea tree will not perform well on alkaline soils and is intolerant of soil salinity.
- **Natural hazards.** Tea tree tolerates flooding and waterlogging. Mature plants can survive several days of total immersion in water without negative side-effects, however seedlings are less likely to survive. Prolonged flooding can result in plantation losses. Tea tree is readily capable of re-growth following a bushfire, although bushfires can be considered less likely to impact on commercial tea tree plantations than flooding.
5. Important weeds in the industry

5.1. Implications of climate and soil requirements for weeds

Tea tree growth rates, and therefore yield, are likely to be significantly lower when the climate and soil conditions discussed in Section 4.4 are not met. This has led the industry to concentrate production in relatively specific high rainfall coastal regions of Australia, either coinciding closely with naturally occurring tea tree populations, or in climatically similar regions. Local awareness was important in initial development of the industry in the Northern Rivers of NSW (Virtue 1997, Colton et al. 2000).

Many of the weeds that co-exist with naturally occurring tea tree are likely to have a competitive advantage within tea tree plantations. Further, the climate and soil requirements of tea tree as summarised above indicate potential characteristics of weeds that are likely to exist in tea tree production systems:

- Growing as a perennial plant, although annual weeds may still be significant if they perform well in the climate most suited to tea tree production (Virtue 1997).
- Tolerance of high temperatures but relatively intolerant of frost or cooler winter climates.
- Preference for high levels of rainfall and high humidity, as well as tolerance of dry early spring conditions, especially relevant to perennial weed species (Virtue 1997).
- Preference for fertile acid or neutral soils that can hold moisture during extended dry weather.
- Tolerance of flooding and waterlogging.

The climate of the Northern Rivers and Mid-North Coast regions of NSW, with reliable summer rainfall and high humidity, favours the growth of herbaceous annual weeds as well as warm-season grasses. Perennial weeds that are capable of persisting through winter and through dry early spring conditions are also favoured (Virtue 1997, Virtue 1999).

5.2. Identifying weeds of tea tree plantations

The predominant weeds found in Australian TTO plantations include a mixture of broadleaf, grass and sedge weeds, mainly annual but with some perennial species also present. Annual weeds are most likely to pose problems for TTO producers in the period following harvest, or more likely during cultivation activities associated with establishment of a new crop. Both activities create bare ground in which annual weeds can germinate. Perennial weeds are often favoured by production systems featuring minimal soil disturbance, a key characteristic of tea tree plantations once they have been established (Virtue 1999).

Table 3.1 lists significant weeds of tea tree plantations as identified in previous research, and preliminary industry consultation.

This list is not exhaustive and in many cases the information is relatively dated. The weeds noted in the table are still likely to be amongst the most important to TTO producers, though industry consultation may reveal other species that have become important in more recent times. The information also focuses strongly on northern NSW industry, and does not account for weed burdens in the Atherton Tablelands, QLD, production area, where producers may face a significantly different suite of weeds (Larkman 2019).

These gaps in knowledge suggest that an updated list of weeds of significance to the industry (including in the Atherton Tablelands) will be of value to guide development of tailored integrated weed management approaches specific to the weeds present and their susceptibility to different management approaches.
Herbicide-resistant grasses have been anecdotally noted in the industry (Larkman 2019). Information on the extent of herbicide resistance in the industry is not available in the literature, however some of the broadleaf weeds listed in Table 5.1 have been noted to be less than fully controlled by certain herbicides on some farms (Sutton et al. 1997), while others have been noted as resistant to certain herbicides in other cropping industries. This information suggests there is considerable potential for herbicide resistance developing within tea tree plantations – if it is not already present.

A survey of herbicide resistance in tea tree plantations, including relevant species, herbicides and locations, may assist in quantifying the extent of the issue, and exploring alternative approaches to managing resistant populations, either with alternative herbicides or using a mixture of non-herbicide approaches.

**Table 3.1 Weed species identified in Australian tea tree plantations in previous research**

<table>
<thead>
<tr>
<th>Weed</th>
<th>Perenniality*</th>
<th>Form</th>
<th>Notes</th>
<th>Information source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bellvine (Ipomoea spp.)</td>
<td>Either Broadleaf herbaceous</td>
<td>Present in the industry.</td>
<td>McMillan and Cook (1994); Virtue (1997); Sutton et al. (1997); Colton et al. (2000)</td>
<td></td>
</tr>
<tr>
<td>Fireweed (Senecio madagascariensis)</td>
<td>Either Broadleaf herbaceous</td>
<td>‘Scattered populations’ amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994); Virtue (1997); Sutton et al. (1997); Colton et al. (2000)</td>
<td></td>
</tr>
<tr>
<td>Native buttercup (Ranunculus spp.)</td>
<td>Either Broadleaf herbaceous</td>
<td>‘Scattered populations’ amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994)</td>
<td></td>
</tr>
<tr>
<td>Oxalis (Oxalis spp.)</td>
<td>Either Broadleaf herbaceous</td>
<td>‘Scattered populations’ amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994)</td>
<td></td>
</tr>
<tr>
<td>Paddy’s lucerne (Sida rhombifolia)</td>
<td>Either Broadleaf herbaceous</td>
<td>‘Scattered populations’ amongst farmers surveyed in NSW. Not considered fully controlled by pre-plant discing in one survey (Sutton et al. 1997).</td>
<td>McMillan and Cook (1994); Sutton et al. (1997); Virtue (1997); Colton et al. (2000); Entwistle (2013)</td>
<td></td>
</tr>
<tr>
<td>Riceflower (Pimelea linifolia)</td>
<td>Either Broadleaf herbaceous</td>
<td>‘Scattered populations’ amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994)</td>
<td></td>
</tr>
<tr>
<td>Scourweed (Sisyrinchium spp.)</td>
<td>Either Broadleaf herbaceous</td>
<td>‘Scattered populations’ amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994)</td>
<td></td>
</tr>
<tr>
<td>Starwort (Aster subulatus)</td>
<td>Either Broadleaf herbaceous</td>
<td>‘Scattered populations’ amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994); Virtue (1997); Colton et al. (2000)</td>
<td></td>
</tr>
<tr>
<td>Tropical chickweed (Drymaria cordata)</td>
<td>Either Broadleaf herbaceous</td>
<td>Present in the industry.</td>
<td>Colton et al. (2000)</td>
<td></td>
</tr>
<tr>
<td>White eclipta (Eclipta prostrata)</td>
<td>Either Broadleaf herbaceous</td>
<td>‘Scattered populations’ amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994)</td>
<td></td>
</tr>
<tr>
<td>Wandering jew (Commelina spp.)</td>
<td>Either Broadleaf herbaceous</td>
<td>Present in the industry.</td>
<td>Colton et al. (2000)</td>
<td></td>
</tr>
<tr>
<td>Common everlasting (Chrysanthemum apiculatum)</td>
<td>Long Broadleaf herbaceous</td>
<td>‘Scattered populations’ amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994)</td>
<td></td>
</tr>
<tr>
<td>Cotton bush (Gomphocarpus spp.)</td>
<td>Long Broadleaf herbaceous</td>
<td>Significant on some farms in NSW.</td>
<td>Entwistle (2013)</td>
<td></td>
</tr>
<tr>
<td>Weed</td>
<td>Perenniality*</td>
<td>Form</td>
<td>Notes</td>
<td>Information source</td>
</tr>
<tr>
<td>------------------------------------</td>
<td>---------------</td>
<td>------------------</td>
<td>----------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Flatweed (Hypochoeris radicata)</td>
<td>Long</td>
<td>Broadleaf herbaceous</td>
<td>Common amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994); Virtue (1997); Colton et al. (2000)</td>
</tr>
<tr>
<td>Gonocarpus (Gonocarpus micranthus)</td>
<td>Long</td>
<td>Broadleaf herbaceous</td>
<td>‘Scattered populations’ amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994)</td>
</tr>
<tr>
<td>Guinea flower (Hibbertia vestita)</td>
<td>Long</td>
<td>Broadleaf herbaceous</td>
<td>‘Scattered populations’ amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994)</td>
</tr>
<tr>
<td>Kidney weed (Dichondra repens)</td>
<td>Long</td>
<td>Broadleaf herbaceous</td>
<td>Common/abundant amongst farmers surveyed in NSW. Not considered fully controlled by hand weeding in one survey (Sutton et al. 1997).</td>
<td>McMillan and Cook (1994); Virtue (1997); Sutton et al. (1997); RIRDC (1999); Colton et al. (2000)</td>
</tr>
<tr>
<td>Kidney weed (Dichondra repens)</td>
<td>Long</td>
<td>Broadleaf herbaceous</td>
<td>Present in the industry.</td>
<td>Colton et al. (2000)</td>
</tr>
<tr>
<td>Pennywort (Centella asiatica)</td>
<td>Long</td>
<td>Broadleaf herbaceous</td>
<td>Present in the industry.</td>
<td>Colton et al. (2000)</td>
</tr>
<tr>
<td>Rorippa (Rorippa laciniata)</td>
<td>Long</td>
<td>Broadleaf herbaceous</td>
<td>‘Scattered populations’ amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994)</td>
</tr>
<tr>
<td>Smartweed (Persicaria spp.)</td>
<td>Long</td>
<td>Broadleaf herbaceous</td>
<td>‘Scattered populations’ amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994); Virtue (1997); Sutton et al. (1997); Colton et al. (2000)</td>
</tr>
<tr>
<td>Spreading bluebell (Wahlenbergia gracilis)</td>
<td>Long</td>
<td>Broadleaf herbaceous</td>
<td>‘Scattered populations’ amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994)</td>
</tr>
<tr>
<td>Willowtop primrose (Ludwigia octovalvis)</td>
<td>Long</td>
<td>Broadleaf herbaceous</td>
<td>Present in the industry.</td>
<td>Colton et al. (2000)</td>
</tr>
<tr>
<td>Annual ragweed (Ambrosia artemisifolia)</td>
<td>Short</td>
<td>Broadleaf herbaceous</td>
<td>Present in the industry.</td>
<td>Colton et al. (2000)</td>
</tr>
<tr>
<td>Apple of Peru (Nicandra physalodes)</td>
<td>Short</td>
<td>Broadleaf herbaceous</td>
<td>Present in the industry.</td>
<td>Colton et al. (2000)</td>
</tr>
<tr>
<td>Blackberry nightshade (Solanum nigrum)</td>
<td>Short</td>
<td>Broadleaf herbaceous</td>
<td>Significant on some farms in NSW.</td>
<td>Entwistle (2013)</td>
</tr>
<tr>
<td>Blue billygoat weed (Ageratum houstonianum)</td>
<td>Short</td>
<td>Broadleaf herbaceous</td>
<td>‘Scattered populations’ amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994)</td>
</tr>
<tr>
<td>Button burweed (Soliva anthemifolia)</td>
<td>Short</td>
<td>Broadleaf herbaceous</td>
<td>‘Scattered populations’ amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994); Virtue (1997)</td>
</tr>
<tr>
<td>Colombian waxweed (Cuphea carthagenersis)</td>
<td>Short</td>
<td>Broadleaf herbaceous</td>
<td>Significant on some farms in NSW.</td>
<td>Colton et al. (2000); Entwistle (2013)</td>
</tr>
<tr>
<td>Farmer's friend (Bidens pilosa)</td>
<td>Short</td>
<td>Broadleaf herbaceous</td>
<td>Significant on some farms in NSW.</td>
<td>Colton et al. (2000); Entwistle (2013)</td>
</tr>
<tr>
<td>Weed</td>
<td>Perenniality*</td>
<td>Form</td>
<td>Notes</td>
<td>Information source</td>
</tr>
<tr>
<td>------------------------------</td>
<td>--------------</td>
<td>--------------</td>
<td>----------------------------------------------------------------------</td>
<td>---------------------------------------------------------</td>
</tr>
<tr>
<td>Fleabane (Conyza spp.)</td>
<td>Short</td>
<td>Broadleaf</td>
<td>Herbaceous Common/abundant amongst farmers surveyed in NSW. Glyphosate-resistant populations noted in other industries.</td>
<td>McMillan and Cook (1994); Virtue (1997); RIRDC (1999); Colton et al. (2000); Charles (2013)</td>
</tr>
<tr>
<td>Purple top (Verbena bonariensis)</td>
<td>Short</td>
<td>Broadleaf</td>
<td>Herbaceous 'Scattered populations' amongst farmers surveyed in NSW.</td>
<td>Virtue (1997); Larkman (2019); Entwistle (2013); Colton et al. (2000)</td>
</tr>
<tr>
<td>Sesbania (Sesbania cannabina)</td>
<td>Short</td>
<td>Broadleaf</td>
<td>Herbaceous Present in the industry.</td>
<td>McMillan and Cook (2000)</td>
</tr>
<tr>
<td>Slender celery (Apium leptophyllum)</td>
<td>Short</td>
<td>Broadleaf</td>
<td>Herbaceous 'Scattered populations' amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994); Virtue (1997)</td>
</tr>
<tr>
<td>Sowthistle (Sonchus oleraceus)</td>
<td>Short</td>
<td>Broadleaf</td>
<td>Herbaceous 'Scattered populations' amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994); Virtue (1997); Charles (2013)</td>
</tr>
<tr>
<td>Spear thistle (Cirsium vulgare)</td>
<td>Short</td>
<td>Broadleaf</td>
<td>Herbaceous Present in the industry.</td>
<td>McMillan and Cook (2000)</td>
</tr>
<tr>
<td>Spreading sneezeweed (Centipeda minima)</td>
<td>Short</td>
<td>Broadleaf</td>
<td>Herbaceous 'Scattered populations' amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994)</td>
</tr>
<tr>
<td>Thickhead (Crasocephalum crepidioides)</td>
<td>Short</td>
<td>Broadleaf</td>
<td>Herbaceous Present in the industry.</td>
<td>McMillan and Cook (2000)</td>
</tr>
<tr>
<td>Ferny buttercup (Ranunculus pumilio)</td>
<td>Short</td>
<td>Broadleaf</td>
<td>Herbaceous 'Scattered populations' amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994)</td>
</tr>
<tr>
<td>Stagger weed (Stachys arvensis)</td>
<td>Short</td>
<td>Broadleaf</td>
<td>Herbaceous 'Scattered populations' amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994)</td>
</tr>
<tr>
<td>Bittercress (Cardamine sp.)</td>
<td>Either</td>
<td>Broadleaf</td>
<td>Herbaceous 'Scattered populations' amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994)</td>
</tr>
<tr>
<td>Native herb (Hypericum gramineum)</td>
<td>Either</td>
<td>Broadleaf</td>
<td>Herbaceous 'Scattered populations' amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994)</td>
</tr>
<tr>
<td>Summer grass (Digitaria spp.)</td>
<td>Either</td>
<td>Grass</td>
<td>'Scattered populations' amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994)</td>
</tr>
<tr>
<td>Giant Parramatta grass (Sporobolus indicus)</td>
<td>Long</td>
<td>Grass</td>
<td>Common/abundant amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994)</td>
</tr>
<tr>
<td>Weed</td>
<td>Perenniaility*</td>
<td>Form</td>
<td>Notes</td>
<td>Information source</td>
</tr>
<tr>
<td>------------------------------</td>
<td>---------------</td>
<td>-------</td>
<td>---------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Paspalum (Paspalum dilatatum)</td>
<td>Long</td>
<td>Grass</td>
<td>Common/abundant amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994); Virtue (1997); Colton et al. (2000)</td>
</tr>
<tr>
<td>Pinrushes (Juncus spp.)</td>
<td>Long</td>
<td>Grass</td>
<td>'Scattered populations' amongst farmers surveyed in NSW. Not considered fully controlled by glyphosate, paraquat/diquat, fluazifop-p, clopyralid+haloxyfop+glufosinate in one survey (Sutton et al. 1997).</td>
<td>McMillan and Cook (1994); Virtue (1997); Sutton et al. (1997); Colton et al. (2000)</td>
</tr>
<tr>
<td>Setaria (Setaria sphacelata)</td>
<td>Long</td>
<td>Grass</td>
<td>'Scattered populations' amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994)</td>
</tr>
<tr>
<td>Slender rat’s tail grass (Sporobulus spp.)</td>
<td>Long</td>
<td>Grass</td>
<td>'Scattered populations' amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994)</td>
</tr>
<tr>
<td>Whiskey grass (Andropogon virginicus)</td>
<td>Long</td>
<td>Grass</td>
<td>'Scattered populations' amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994)</td>
</tr>
<tr>
<td>Barnyard grass (Echinochloa crus-galli)</td>
<td>Short</td>
<td>Grass</td>
<td>Present in the industry.</td>
<td>Colton et al. (2000)</td>
</tr>
<tr>
<td>Crab grass (Eleusine indica)</td>
<td>Short</td>
<td>Grass</td>
<td>Present in the industry.</td>
<td>Colton et al. (2000)</td>
</tr>
<tr>
<td>Pale pigeon grass (Setaria glauca)</td>
<td>Short</td>
<td>Grass</td>
<td>Present in the industry.</td>
<td>Colton et al. (2000)</td>
</tr>
<tr>
<td>Sedges (Cyperus spp.)</td>
<td>Either</td>
<td>Sedge</td>
<td>Common/abundant amongst farmers surveyed in NSW. Especially problematic in wetter soils. Not considered fully controlled by paraquat/diquat, clopyralid+haloxyfop+glufosinate in one survey (Sutton et al. 1997).</td>
<td>McMillan and Cook (1994); Virtue (1997); RIRDC (1999); Colton et al. (2000); Entwistle (2013); Larkman (2019)</td>
</tr>
<tr>
<td>Small rush (Isolepis inundata)</td>
<td>Long</td>
<td>Sedge</td>
<td>‘Scattered populations’ amongst farmers surveyed in NSW.</td>
<td>McMillan and Cook (1994)</td>
</tr>
</tbody>
</table>

* Short = short perenniality (annual/biennial); Either = either perenniality (annual/biennial or perennial); Long = long perenniality (perennial).
6. Impact of weeds on tea tree production

Weed control is considered a very important aspect of crop management in tea tree (Virtue 1997). They are considered a major limitation to tea tree production (RIRDC 1999), and the major cause of poor crop establishment or crop failure (Colton & Murtagh 1990, McMillan & Cook 1994).

The most significant potential competition from weeds within tea tree crops occurs during the first two months after planting (McMillan & Cook 1994). Where high weed densities are present during this period and in the following months of crop establishment, yield losses of up to 97% can occur (RIRDC 1999). In an industry survey, growers on average indicated yield losses of 64% may be expected if weeds were not controlled (Virtue 1997).

Experiments have shown that weed interference can reduce TTO yield in established crops from 9 to 47% (Virtue et al. 2000), while growers have estimated uncontrolled weed outbreaks in established crops may result in crop yield reductions of over 50% during the annual regrowth phase (Virtue 1997). Impacts of weeds on TTO production can include (Sutton et al. 1997, Virtue 1997, Virtue 1999):

- Competition for light, moisture and nutrients, especially significant in recently established tea tree plantations, but also important following harvest and regrowth of tea tree plants, particularly after spring harvest when weeds are most likely to germinate and grow. Weed interference in the early stages of growth or re-growth can significantly reduce tea tree leaf density and yield, and therefore yield at harvest.
- A potential allelopathic effect that may hinder growth of recently planted tea tree specimens, with several weed species known to release allelopathic compounds found in plantations.
- The potential for weed biomass collected during harvest to dilute or taint the purity of TTO during the distillation process (Tea Tree Traders Codrington 2014), although research by Virtue et al. (2000) suggested weeds did not significantly impact the chemical composition of the TTO.

6.1. Economic impact

Virtue (1999) provided two examples of the impact of weed interference in tea tree crop yield, assuming two different planting densities and a fixed per-tree mature harvest oil yield (Table 4.1).

<table>
<thead>
<tr>
<th>Planting density (trees per hectare)</th>
<th>Mature harvest oil yield (assumed; per tree)</th>
<th>Yield reduction per tree due to weed interference (assumed)</th>
<th>Yield reduction ($ per hectare, 1999*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15,000</td>
<td>8 g</td>
<td>40%</td>
<td>$2,160</td>
</tr>
<tr>
<td>30,000</td>
<td>8 g</td>
<td>25%</td>
<td>$2,700</td>
</tr>
</tbody>
</table>

* Price assumed by the authors of AU$45 per kg.

Data on the direct costs of managing weeds in tea tree were not available in the literature, but will include machinery purchase, operation and maintenance, chemicals, and labour. Other expenses such as those related to livestock management or cover cropping may be relevant if these or other practices are included in a TTO producer’s IWM approach.
6.2. Impact on crop yield

Virtue (1997) conducted a series of field experiments at four sites in Northern NSW on the impact of weed interference on tea tree yield, with a focus on their competition with the crop during the post-harvest regrowth cycle. Key findings (details also available in Virtue 1999) included:

- **Timing:** weed competition appears to have the greatest detrimental impact on mature tea tree yield late in the crop regrowth cycle. Specifically, across the four sites where experiments were completed, the period of greatest weed interference occurred between 6 and 10 months after harvest.

- **Weed competition for light** appeared to be an important factor in tea tree yield reductions, though this issue is most likely to be significant early in the post-harvest regrowth cycle.
  - In some of the field experiments completed, tea trees which were shaded by weeds during the early stages of regrowth were set back for the remainder of the regrowth period, with mature leaf yield losses of up to 20% noted. This suggests that tea tree is poorly adapted to shading. Tea tree crops are most susceptible to shading during early stages of regrowth, when weeds and crop shoots are at a similar height.
  - Susceptibility to shading by weeds, and therefore reduction in yield appeared to be greater when the post-harvest regrowth period commences in relatively cool periods (such as an autumn harvest). In these conditions, lower temperatures slow down crop re-shooting. Conversely, harvesting in late summer appeared to allow relatively rapid shoot growth and emergence, reducing the risk of weeds shading out the crop and therefore reducing their impact on subsequent yield.
  - Dominant weeds present in the field appear to have implications for the extent of weed competition with the tea tree crop for light. For example, where the dominant weeds were of relatively short stature, slower regrowth brought about by an autumn harvest was a less important issue than in fields where taller-stature and high biomass weeds were prevalent.

- **Weed competition for nutrients,** particularly soil nitrogen, was identified in three of the four experimental sites, whereas competition for phosphorus and potassium was identified at one site.
  - The high root density of herbaceous weeds, in comparison to the regrowth tea tree crop, was suggested as an important factor in their ability to compete for and absorb soil nutrients.
  - The main period of weed competition with tea tree crops for soil nutrients appeared to be in the second half of the regrowth period (spring and summer) when there is greater inter-shoot competition for soil nutrients.

- **Weed competition for soil moisture** with the tea tree crop was not identified as a significant issue, although some reduction in soil moisture was noted due to the presence of weeds. The author suggested that this may be due to the capacity of established tea tree to access water at depth due to its root structure, and the relatively high soil water table on the north coast of NSW where the competition trials took place. In plantations where a high soil water table is absent, tea tree crops may face greater competition from weeds to access available soil moisture from rainfall or irrigation events.

- Although research does not appear to have been carried out on allelopathic effects of weeds on tea tree, these may restrict crop growth by slowing water and nutrient uptake and inhibiting photosynthesis. Younger tea tree plants would be more susceptible, due to their smaller root systems. Several weeds commonly found in tea tree plantations are known to release allelochemicals, including couch (*Cynodon dactylon*), farmer’s friend (*Bidens Pilosa*), barnyard grass (*Echinochloa crus-galli*) and summer grass (*Digitaria sanguinalis*).
6.3. Impact on oil quality

The industry considers weed control important in reducing the risk of weeds tainting the quality of oil harvested from the tea tree crop (e.g. Tea Tree Traders Codrington 2014). However, research exploring the chemical composition of tea tree oil harvested from weedy and weed-free plots did not identify any significant differences. The authors of this study also noted that since weeds are likely to form a very small proportion of the harvested material in a tea tree crop, essential oils drawn from weeds during the distillation process will be heavily diluted by the target tea tree oil (Virtue et al. 2000).

McMillan and Cook (1994) tested several pre-emergent herbicides for their effect on oil quality through contamination, as part of a larger herbicide screening project. In some cases, herbicides were applied at up to three times the normal recommended rate. Furthermore, the trial plots were sampled relatively shortly after establishment (3-6 months) compared to the normal 9-24 months found in commercial plantations. Despite these factors, the authors did not find any herbicide residue in the oil samples tested.

6.4. Impact on crop and farm management

Weeds have the potential to host pests and diseases of tea tree, though this appears to be relatively unlikely. Relatively heavy weed burdens in the paddock, or vine weeds, may interfere with harvest activity, and reduce harvest efficiency (Colton et al. 2000, Virtue et al. 2000).
7. Current weed control approaches

Methods used to control weeds in tea tree plantations can include herbicides, cultivation, mowing or slashing, grazing, green manure/cover crops, mulches, or burning (Sutton et al. 1997). Preventive techniques are also appropriate, to restrict as much as possible the spread of new weed propagules (weed seed or reproductive plant parts) into the plantation – for example through diligent and effective farm hygiene (Virtue 1999, Prastyono 2008).

Weed control practices which are common to annual cropping systems, such as fallow cultivation or herbicide application, and crop rotation (to allow different weed species to be managed) are not available in perennial tea tree crops (Barney & Finnerty n.d.). Consequently, tea tree weed management is more difficult than in these annual systems.

An effective weed management strategy in tea tree plantations will use a range of practices, and accounts for time of year, weed species present, and crop life stage (Virtue 2006).

7.1. Phases of weed control in tea tree plantations

Sutton et al. (1997) identify two distinct phases of weed management in tea tree plantations. Each of these phases involves using a different mix of weed control methods and some methods will be more relevant to one phase than the other.

7.2. Weed control from establishment to first harvest

Weed control during crop establishment involves preparing the ground for initial planting of the tea tree crop by reducing the weed seed bank and minimising the number of weeds present in the soil. In perennial crops such as tea tree, this is especially important in the case of perennial weeds, which can be more difficult to manage once the crop has been established (Madge 2007, Miller n.d.).

Site preparation weed management should start at least 12 months before the crop is planted, using cultivation and/or herbicides as appropriate (Sutton et al. 1997, Colton et al. 2000, Unknown 2009, UC IPM 2017, Barney & Finnerty n.d., Miller n.d.).

- **Non-selective herbicides** such as glyphosate should be applied to perennial weeds before cultivation is used. This is especially relevant to hardy weeds such as nutgrass (*C. rotundus*) and couch (*C. dactylon*), which are readily able to re-establish from plant parts following a single cultivation pass. Annual weeds should be controlled on the site before they produce seed, to aid with weed seed bank reduction.

- **Several cultivation passes** may be used to reduce the weed seed bank (see also Section 7.5.1) however excessive cultivation will contribute to a break down in soil structure. Cultivating the field approximately five days after herbicide application will assist with perennial weed control, as the physical damage of cultivation can work with herbicide activity on these weeds to further reduce their chance of re-sprouting. Cultivation will be at its most effective when the soil is very dry, especially regarding perennial weeds capable of re-establishing from severed plant parts.

- **Pre-emergent residual herbicides** are strongly recommended to manage weeds at the time of planting.

Seedling tea tree crops are particularly susceptible to weed competition and require a weed-free period of approximately 12 weeks after planting to ensure successful establishment. By that stage, the crop will have started to achieve ‘reasonable ground cover’ and be able to compete with weeds more effectively through to first harvest. It is vital to manage weeds effectively in newly established plantations, with the goal of maximising weed control until the first harvest (Colton & Murtagh 1990, Virtue 1999, Colton et al. 2000). Following planting and while the seedling crop is establishing, selective and/or shielded inter-row herbicides and inter-row cultivation should be used to minimise...
weed germination. Some farmers may also use some hand weeding, mowing, or grazing in the period between planting and first harvest (Sutton et al. 1997). Competition from weeds will likely continue in a newly established plantation until canopy closure, approximately 9-12 months after planting (Colton et al. 2000).

### 7.3. Weed control during the annual regrowth cycle

After the initial harvest, a long-term annual cycle of plant shoot re-growth and harvest takes place. Within this cycle, the critical period of weed control tends to be in the first few weeks after harvest to control existing weeds, and before the crop canopy has closed again, to control newer weed cohorts. This is not only because weeds can compete with the re-shooting crop, but also because the bare ground created by harvest gives annual and perennial weeds an opportunity to germinate and grow quickly. At the same time, the immediate post-harvest period provides a good opportunity to manage annual and perennial weeds effectively. Good weed management during this time will reduce weed competition later in the crop regrowth cycle (Virtue 1999, Colton et al. 2000).

Weed control methods may include post-harvest non-selective herbicide, selective herbicide within the regrowing crop, mulching, effective weed suppression in the inter-row space, and potentially shallow inter-row cultivation and grazing. The goals are to minimise the impact of weeds on re-growth yield, and minimise weed contamination of the next harvest (Virtue et al. 1993, Sutton et al. 1997, Virtue 1997, Virtue 1999).

### 7.4. Herbicides

Herbicides are considered the most effective and affordable weed management technique in tea tree plantations. They provide better value for money than hand weeding and mowing/slashing in particular (Sutton et al. 1997, Virtue 1999), and are also considered to be the cheapest weed control option in other coppiced crops (Unknown 2009). Herbicide usefulness is maximised when used in conjunction with other techniques (Colton et al. 2000).

Herbicides are particularly important during bed preparation for a new crop, and to protect recently planted crop seedlings. Pre-emergent residual herbicides are applied to the soil surface to control germinating weeds just prior to planting of tea tree seedlings (pre-sowing pre-emergence) or immediately after planting (post-sowing pre-emergence). Products which control a broad spectrum of broadleaf and grass species are most suitable, and good control of a wide range of weeds can be expected for up to 12 weeks after application (Virtue 1999, Colton et al. 2000). Additional residual herbicide options may expand the options available to producers to effectively control annual and perennial weeds over an extended period (Harrington 2000), but the potential for these to damage the crop would need to be explored further.

Within an established tea tree crop, post-emergent herbicides may be used to control weeds between crop rows (the inter-row space), directed away from the tea tree plants using shielded spray equipment to avoid crop damage. Some post-emergent selective herbicides are also available for over the top application to control a specific range of weed species. Non-selective herbicides may also be used over the top of the crop following harvest and before coppicing (re-growth), where few if any crop leaves are available to translocate the herbicide. Many producers use a broad-scale application of either glyphosate or paraquat/diquat soon after harvest, both non-selective herbicides that are applied with the goal of controlling weeds in the bare coppiced crop before the crop starts to re-shoot (Sutton et al. 1997, Virtue 1999, Larkman 2019). In all cases, herbicides are used to manage weeds that have already established in the crop (Colton et al. 2000).

Over the top and shielded inter-row options are registered or permitted to control broadleaf and/or grass weeds in tea tree plantations in Australia (Table 5.1).
7.4.1. Product availability

The motivation of the chemical industry to research and register herbicides for relatively small-scale specialty crops such as tea tree will most likely be restricted by the limited potential value of sales, and therefore the potential return on investment in the cost of registration (Fennimore & Doohan 2008). Minor use permits are therefore the most likely way in which the industry can access additional herbicide options once relevant testing has been carried out.

At the time of writing, the ATTIA Pesticide Guide for Tea Tree Growers (ATTIA 2020) listed several herbicides that were fully registered for use within tea tree crops, as well as a larger number that were available to growers under an APVMA minor use permit (PER82090; valid until 31 July 2023). The herbicide 2,4-D is available under a separate minor use permit (PER87174). These products have been summarised below in Table 5.1. The summary includes the timing of application relevant to crop growth stage, either within the tea tree crop (if fully registered for tea tree crop application) or within other crops (if available under PER82090).

<table>
<thead>
<tr>
<th>Herbicide active ingredient</th>
<th>Herbicide group</th>
<th>Crop growth stage</th>
<th>Registration status</th>
<th>Weeds controlled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haloxyfop</td>
<td>A</td>
<td>Post-emergence (2nd leaf onwards)</td>
<td>Minor use permit</td>
<td>Various perennial and annual grass weeds.</td>
</tr>
<tr>
<td>Trifluralin</td>
<td>D</td>
<td>Pre-emergence</td>
<td>Minor use permit</td>
<td>Various grass and annual broadleaf weeds.</td>
</tr>
<tr>
<td>Simazine</td>
<td>C</td>
<td>Pre-emergence or in established tree and vine crops</td>
<td>Minor use permit</td>
<td>Various grass and annual broadleaf weeds.</td>
</tr>
<tr>
<td>Metolachlor</td>
<td>K</td>
<td>Pre-emergence or immediately post-transplant</td>
<td>Minor use permit</td>
<td>Various grass and annual broadleaf weeds.</td>
</tr>
<tr>
<td>Glyphosate</td>
<td>M</td>
<td>Non-selective (fallow or pre-plant/pre-sowing)</td>
<td>Minor use permit</td>
<td>For general weed control.</td>
</tr>
<tr>
<td>2,4-D</td>
<td>I</td>
<td>Pre- or post-emergence (directed shielded spray).</td>
<td>Minor use permit</td>
<td>Various broadleaf weeds, including a number noted in Table 5.1.</td>
</tr>
<tr>
<td>Linuron</td>
<td>C</td>
<td>Pre- or post-emergence depending on crop; directed shielded spray.</td>
<td>Minor use permit</td>
<td>Various grass and annual broadleaf weeds.</td>
</tr>
<tr>
<td>Flupropanate</td>
<td>J</td>
<td>Selective control, especially soon after harvest.</td>
<td>Minor use permit</td>
<td>Various grass weeds.</td>
</tr>
<tr>
<td>Clopyralid</td>
<td>I</td>
<td>Pre-sowing to post-emergence (directed shielded spray onto actively growing weeds).</td>
<td>Minor use permit</td>
<td>Various broadleaf weeds.</td>
</tr>
<tr>
<td>Glufosinate ammonium</td>
<td>N</td>
<td>Non-selective (fallow or pre-plant/pre-sowing); directed shielded spray.</td>
<td>Full registration</td>
<td>For general weed control.</td>
</tr>
<tr>
<td>Oxyfluorfen</td>
<td>G</td>
<td>Inter-row directed application.</td>
<td>Minor use permit</td>
<td>Various broadleaf weeds and some grass weeds.</td>
</tr>
<tr>
<td>Herbicide active ingredient</td>
<td>Herbicide group</td>
<td>Crop growth stage</td>
<td>Registration status</td>
<td>Weeds controlled</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>----------------</td>
<td>------------------</td>
<td>--------------------</td>
<td>-------------------------------------------</td>
</tr>
<tr>
<td>Atrazine</td>
<td>C</td>
<td>Pre- or post-emergence (directed shielded spray).</td>
<td>Minor use permit</td>
<td>Various annual grass and broadleaf weeds.</td>
</tr>
<tr>
<td>Fluazifop</td>
<td>A</td>
<td>Post-emergence</td>
<td>Full registration</td>
<td>Annual grasses (except Poa annua and Vulpia spp.).</td>
</tr>
<tr>
<td>Paraquat/diquat</td>
<td>L</td>
<td>Immediately post-harvest</td>
<td>Full registration</td>
<td>Various grass and broadleaf weeds.</td>
</tr>
<tr>
<td>2,2-DPA</td>
<td>J</td>
<td>Apply to seedling trees or immediately post-harvest, or directed to the base of trees</td>
<td>Full registration</td>
<td>Annual and perennial grass weeds.</td>
</tr>
<tr>
<td>Pendimethalin</td>
<td>D</td>
<td>Pre-transplant or immediately post-transplant</td>
<td>Full registration</td>
<td>Various grass and broadleaf weeds.</td>
</tr>
<tr>
<td>Oryzalin</td>
<td>D</td>
<td>At time of planting or immediately post-harvest</td>
<td>Full registration</td>
<td>Various grass and broadleaf weeds.</td>
</tr>
</tbody>
</table>

**7.4.2. Weed control success and viability**

Successful control of weeds in tea tree plantations using herbicides (Colton et al. 2000) may be maximised by:

- Applying herbicide to actively growing weeds that are not stressed due to lack of moisture, waterlogging or frost.
- Spraying in cooler, still conditions (early morning or late evening) improves herbicide absorption and reduces the risk of spray drift.

A 1992 industry survey (Sutton et al. 1997) found that most TTO producers used *non-selective herbicides* to control weeds in the seed bed prior to planting, and in the period between planting and first harvest. At these stages of the crop cycle, herbicides such as the most commonly used products at the time (glyphosate, paraquat/diquat and oryzalin + metolachlor) were found to give good, though not complete, control of weeds for up to four weeks. Minimal crop damage was noted, except for the application of herbicides clopyralid + haloxyfop + glufosinate, which together were found to result in significant crop damage.

*Pre-emergent herbicides* are vital in ensuring good initial establishment of the tea tree crop, and higher initial yield. Research by McMillan and Cook (1994) found a 40-fold yield difference between removing weeds 31 days after planting a tea tree crop, compared to 147 days after planting.

Within the annual regrowth cycle, Sutton et al. (1997) found in their 1992 industry survey that an average of 2.7 herbicide applications were used, with paraquat/diquat the most commonly used product after harvest. Weed control was considered ‘above average’ and lasting for up to several months with little damage to the crop. Generally, *post-emergent herbicide* will be less effective when used to control more mature and/or larger weeds, and higher application rates may be required. Therefore, post-emergent herbicide use should be applied when weeds are relatively small (McMillan & Cook 1994).

Entwistle (2013) noted that it can be difficult to control broadleaf weeds within tea tree crops due to lack of post-emergent herbicides in particular (see also Table 5.1). He trialled several post-harvest pre-emergent herbicides in established tea tree crops, including several that are currently available to producers through the minor use permit PER82090:
Simazine was found on one farm in NSW to be the most effective herbicide of several trialled, notably for its capacity to manage the most important weed on the trial farm, *Cuphea carthagenensis*.

Metolachlor was found to be suited to ongoing control of sedges (*Cyperus* spp.) while other products evaluated declined in their performance in managing this weed family.

Linuron was found to be relatively effective in managing *C. carthagenensis* in coppiced tea tree (post-harvest pre-emergence). This herbicide also performed well in a second trial as a selective post-emergent broadleaf option, with minimal phytotoxic impacts on the tea tree crop. Linuron is currently available for both pre- and post-emergent use under the minor use permit.

Glufosinate and paraquat/diquat appear to be relatively effective when used for shielded inter-row weed control in tea tree crops, including providing good control of *Verbena* spp. and *Gomphocarpus* spp. Both also show satisfactory phytotoxic effects on the tea tree crop (Entwistle 2013). At the time of writing, glufosinate may be applied via directed shielded application under the minor use permit, while paraquat/diquat has full registration within tea tree crops (Table 5.1).

Paraquat/diquat appears to be widely used in the industry, but perennial weeds in particular can re-establish quickly from an application of this herbicide (Sutton et al. 1997), as it acts as a desiccant herbicide killing any green plant tissue it comes into contact with. By contrast, glyphosate is a systemic herbicide absorbed via green tissue and translocated throughout the entire plant. Glyphosate is therefore likely to be more effective in controlling both annual and perennial weeds, whereas paraquat/diquat will be more effective in controlling ‘softer’ annual weeds (O’Hare 2004). Nonetheless, Entwistle (2013) noted that industry use of paraquat/diquat as a directed spray herbicide was likely to increase further given the ability to use it safely within the tea tree crop.

Herbicides have been rated as highly effective in managing annual, perennial and woody weeds in forestry production, more than alternatives such as mowing, cultivation and mulches (Vasic et al. 2012).

In blueberries (WSU Whatcom County Extension n.d.) *good record keeping* is considered a key component of ensuring maximal success using herbicides registered for the crop. This includes keeping accurate records of which herbicides were applied, where and at what rate. It is also important to assess their effectiveness post-spraying and monitor for any signs of resistance. Such records will eventually help producers to understand the herbicide/s that achieve the best results in their plantation. These lessons also seem quite relevant to tea tree production.

Organic bioherbicides such as pelargonic acid, acetic acid and citric acid have been proposed for some time as a potential replacement for chemical herbicides, however they are considered less effective than chemical herbicides, and control largely limited to recently germinated weeds. Repeated treatments are also usually required, increasing their overall cost (Lisek 2014).

### 7.4.3. Crop damage

The risk of herbicide damage to tea tree crops can be reduced in several ways. Full details are available in McMillan and Cook (1994), pages 28-29, and it is likely that growers have widely adopted the recommended practices:

- Use directed or shielded application techniques rather than blanket spraying, to minimise tea tree uptake of herbicide via leaves.
- Ensure that post-harvest herbicide applications take place before the trees begin to bud. Be aware that any old growth remaining after harvest may be capable of absorbing post-harvest herbicide application into the crop.
- Avoid applying pre-emergent herbicides when soils are dry.
- Lower application rates may be considered, bearing in mind this could come at the cost of reduced weed control effectiveness.
- Unregistered tank mixtures should be avoided, as these tend to fail industry safety requirements.
7.5. Mechanical

7.5.1. Cultivation

Cultivation is used during bed formation prior to crop planting (see Section 7.2). It may also be used between crop rows (inter-row cultivation), although this practice appears to be primarily limited to recently established plantations, where it may be used before the first harvest and where the crop roots have not had a chance to spread significantly into the inter-row space (Sutton et al. 1997, Virtue 1997).

Pre-plant cultivation is considered effective in managing weeds in plantations before planting and during seedling bed preparation, where approximately five tillage passes may be completed. Pre-plant cultivation may be relatively intense, involving relatively deep passes and a mixture of disc and rotary implements aimed at producing a loose seedling bed suited for planting. Weed control may be effective for up to two months (Sutton et al. 1997, Virtue 1997, Virtue 1999).

Inter-row cultivation within a recently planted crop aims to produce relatively shallow soil disturbance to kill recently germinated weeds, without damaging the tea tree crop roots that have not yet spread into the inter-row space. Cultivation is most effective when used to control recently germinated weed seedlings. Tined or bladed implements are likely to be used. Most weeds can be controlled by cultivation when the soil is relatively dry (to reduce the risk of re-establishment from cultivated plant part) (Virtue 1997, Colton et al. 2000, DeKay 2018, Bradshaw 2019).

Within established crops, mechanical weed control using inter-row cultivation may be conducted using a tined implement, to a depth of 5-10cm, ideally disturbing only the top 1-3cm of soil. A 1992 survey suggests that inter-row cultivation during the annual regrowth period was ‘average to good’, with the benefits lasting for approximately one month (Sutton et al. 1997).

Inter-row cultivation was reported by Sutton et al. (1997) to be used by approximately half the growers surveyed, however it is likely that this proportion has reduced over time, particularly as the range of herbicides available to producers has increased. For example, only four herbicide options were available to TTO producers in 1990 (McMillan & Cook 1994).

Advantages

Inter-row cultivation is considered to have several potential advantages over herbicide use (McMillan & Cook 1994, DeKay 2018):

- It controls weeds relatively quickly, compared to herbicides, therefore removing competition for the tea tree crop immediately.
- Cultivation controls all weeds (providing they do not have extensive or deep root systems or are capable of reproduction from plant parts), whereas selective herbicides in particular may allow some weeds (or weed species) to survive within the crop.
- Cultivation does not leave herbicide residues in the soil and can reduce reliance on herbicides.
- Cultivation can provide crop management benefits, including soil aeration, improved water absorption, and root growth.

Post-plant inter-row cultivation may also be used in conjunction with herbicides to increase the effectiveness of subsequent herbicide application and overall weed management efficacy, by damaging the roots of the weeds. Its effectiveness has been shown in other crops to be further increased (alongside herbicide application) by use of precision guidance technology during the cultivation pass (Kunz et al. 2015, Corteva Agriscience 2019).
Disadvantages


- Soil disturbance can encourage new cohorts of weeds (particularly annual weeds) by bringing weed seed closer to the surface. Spread of certain perennial weeds such as *C. rotundus* and *C. dactylon* may be facilitated by cultivation, breaking up the plant parts which can re-establish vegetatively as new individuals. However, many more advanced perennial weeds, with their deeper root systems, will be relatively unaffected by cultivation.

- Where the goal is ensuring only recently germinated weeds are present in the inter-row space, several cultivation passes will be required each season before weeds become too large, resulting in increased expense and time required and potentially having detrimental impacts on the soil. However, this frequent shallow cultivation approach may also be beneficial in eventually reducing the weed seed bank.

- Soil moisture must be optimal for cultivation to be carried out. It can be difficult to undertake in waterlogged soils often found in plantations, and likewise during dry conditions. Both occasions are commonly observed in tea tree plantations. Waterlogging may also restrict the ability of machinery to get onto the paddock for cultivation in a timely manner. Finally, attempting to cultivate wet soils contributes to soil compaction.

- Cultivation is considered by growers to be less cost-effective once the tea tree plantation has been established, but still more cost-effective than hand weeding or mowing/slashing the inter-row space. Labour and machinery costs are likely to be higher than for herbicide application.

- Damage to crop roots may occur if cultivation is carried out within the crop root zone of an advanced tea tree crop. Similar results have been found in orchard production systems, where herbicide-controlled crop rows result in higher-yielding trees than cultivation-controlled rows. Deep inter-row cultivations may sever the thick lateral roots of the trees. Feeder roots that proliferate around the base of the trees and may extend into the inter-row space are particularly susceptible to damage, particularly if frequent inter-row cultivation were carried out over a longer term. Ongoing feeder and lateral root damage will eventually cause the deeper root system of trees to become dominant reducing the capacity of the crop to access nutrients.

- By creating bare soil, inter-row cultivation may raise the soil temperature in the hottest months to the extent where crop root activity declines.

- Some crop plant spacings may make inter-row cultivation unfeasible in tea tree with equipment available on the farm.

- Inter-row cultivation will make cover cropping or mulching of the inter-row space (Section 7.5.1 and 7.6.1) impractical.

- Cultivation is slower and uses more fuel than equivalent herbicide application.

- Initial passes will be particularly slow, especially if commencing in an established crop where soil compaction has resulted in a ‘hard’ surface layer.

- Regular cultivation can increase the risk of soil compaction because of follow-up machinery activity.

- Since cultivation does not have a residual effect (unlike herbicide) several inter-row cultivation passes may be required over time to maximise the chance of success.

- In the longer-term, regular inter-row cultivation may degrade soil structure and soil organic matter within the plantation, eventually reducing the productivity of the site. The longer-term sustainability of cultivation in tree crops in general has been called into question for this reason.
7.5.2. Mowing/slashing

Mowing is used to reduce the competitiveness of weeds with the crop, by cutting weeds in the inter-row space near ground level. It can also assist in managing and eventually reducing the weed seed bank, by limiting the number of weed seed produced. Keeping a relatively thick weed ‘carpet’ may actually prevent taller weeds from growing and producing seed (Colton et al. 2000, Kawate & Tarutani 2006). However, mowing is ineffective for killing most weeds present, as the growing point of weeds will generally be below the cutting height (Virtue 1999). It is also considered to be relatively poor value for money with regards to weed control in comparison to herbicides, inter-row cultivation or grazing (Sutton et al. 1997).

In a trial conducted by Sutton et al. (1997), mowing was found to be effective in suppressing weed growth for an average of six weeks. This result was similar when mowing was used in the period between planting of a new crop and first harvest, but also during the post-harvest regrowth cycle.

Several mowing passes are likely to be required to suppress weed growth and weed seed production (Yarborough 2011, Kuwar 2012, Vasic et al. 2012), but repeated passes are unlikely to fully control (kill) many perennial weeds residing in the inter-row. Mowing also cannot be used to manage weeds within the crop rows themselves (Sutton et al. 1997).

Advantages

Benefits of mowing weeds between the tea tree crop rows include increasing soil organic matter levels to improve nutrient cycling and soil structure, assisting trafficability and preventing erosion through ground cover. Mown soils may also remain cooler than bare soils during summer (Virtue 1999, Colton et al. 2000, Kawate & Tarutani 2006). If bare inter-row spaces are desired, mowing may be used several months prior to a herbicide application, as more effective control may be obtained on relatively recent perennial weed regrowth (Corteva Agriscience 2019).

Disadvantages

Nonetheless, mowing has a few drawbacks. For example, it contributes to higher weed root density of weeds, potentially allowing weeds to compete more effectively with the crop for soil nutrients (Virtue 1999, Colton et al. 2000). To remain effective at suppressing above-ground crop and weed competition, mowing must be carried out regularly and constantly, or at least when weeds are actively growing and producing seed. This will add to the costs of weed management via fuel use, machinery wear and maintenance, and labour requirements (Kawate & Tarutani 2006, Bekkers 2011).

Over time, lower-stature competitive perennial grasses such as *C. dactylon* may be favoured by repeated mowing, and these will become increasingly dominant in the mown inter-row space. Their vigorous response to mowing, combined with a high root density, makes perennial grasses strongly competitive with the crop for soil nitrogen (Virtue 1999). Similarly, in forestry systems mowing is considered less effective in managing perennial broadleaf and grass weeds and woody weeds, compared to annual broadleaf and grass weeds (Harrington 2000).

In orchard and viticultural production systems, it is common to maintain a narrow weed-free strip along the tree row using herbicides, while mowing between the rows (Harrington 2000). However, Virtue (1997, 1999) found that the inter-row strip in tea tree plantations was narrow enough that it was not possible to avoid mown weed competition with the crop for soil nitrogen. Mowing may even result in equivalent or lower tea tree crop yield than where weeds are left uncontrolled, by increasing weed root density within the inter-row space (Virtue 1997). This conclusion is supported in other similar cropping systems (e.g. forestry), where mowing is considered to have little beneficial effect on weed capacity to compete with tree seedlings (Harrington 2000, Private Forests Tasmania 2017).
7.5.3. Hand weeding

Hand weeding is considered by growers to be relatively poor value for money in comparison to herbicides, inter-row cultivation and grazing (Sutton et al. 1997). Due to its high cost, it is only recommended in tea tree and other crops for ‘spot-weeding’ (for example, of new weed outbreaks, particularly impactful individual weeds, or in order to remove weeds with seed heads from the paddock to reduce the weed seed bank) (Virtue 1999, Kuwar 2012).

Hand weeding has been found to provide effective control against weeds for up to 7 weeks in field experiments but is relatively less effective when used to manage woody perennial weeds due to their relatively extensive root system. It is also relatively labour intensive, and therefore more costly of weed practices available to tea tree producers. However, it may still be the only choice to remove problematic weeds, particularly within the crop row (Sutton et al. 1997, Kuwar 2012, Barney & Finnerty n.d.).

7.6. Cultural

7.6.1. Mulch

Organic mulches can deliver excellent weed control within tea tree rows and in the inter-row space. However, the mulch layer must be sufficiently thick or suppressive so that weed germination and growth minimised through light suppression (Virtue 1999). More mature perennial weeds are considered particularly effective at growing through organic mulch layers due to their extensive root systems, however mulch achieves good control of recently germinated weeds (Yarborough 2011).

This indicates that to maximise its effectiveness, mulch should be applied to a paddock that has already been well managed for established weeds (Private Forests Tasmania 2017). Virtue (1999) also suggests maximising the cost-effectiveness of tea tree litter mulch by applying a relatively thin layer.

7.6.1.1. Advantages

Mulch provides several benefits to TTO producers in addition to weed control, including reducing soil temperature during summer, reducing soil erosion, facilitating rainfall infiltration and reducing evaporation rates, and improving soil nutrients and organic matter. Several organic mulch products may be selected by TTO producers, such as straw or sugar cane. However, tea tree litter that has been through the distillation process provides a ready supply of mulch to all TTO producers. If applied to a reasonable thickness (for example, 100mm) excellent weed control may be achieved (Virtue 1999).

Some TTO producers have been using tea tree litter as a mulch within their crop for many years with success, suppressing weeds but also returning organic matter to the soil (Larkman 2019). Where feasible, using tea tree litter as a mulch appears to have some potential to improve weed management, and will provide benefits in the area of soil improvement.

7.6.1.2. Disadvantages

However, post-distillation tea tree litter mulch has several drawbacks which may make it an impractical option for some TTO producers (Virtue 1999, Colton et al. 2000, Madge 2007, Lisek 2014, Larkman 2019, Barney & Finnerty n.d., Lanini & Grant n.d., Rom & et al. n.d.):

- Many TTO producers distil their tea tree harvest off-site. Returning the post-distillation litter can be cost-prohibitive relative to potential economic benefits, particularly if distillation takes place a considerable distance away. Using tea tree litter as a mulch may be most affordable and practical to those who have on-farm distillation equipment.
- Any organic mulch will only last a limited time (possibly up to 2-3 seasons in tea tree plantations depending on application thickness) and will need to be replenished over time. In other perennial row crops, mulch thickness is found to reduce by up to 60% in the first year after application.
• Application is time-consuming and requires specialised spreading equipment, adding significant cost to crop management.
• Organic mulches such as tea tree litter may not suppress all perennial or more mature weeds. Mulch can also potentially stimulate weed growth through the benefits it provides to soil health and nutrition, particularly as it begins to break down.
• It is more difficult to apply fertiliser to the crop when mulch is already present.
• The tea tree litter may have an allelopathic effect on the crop (though it is not certain from the literature whether any such effect has been explored in field or glasshouse trials).
• Any decision to use tea tree litter as a mulch within the crop means that the producer is missing out on an opportunity to sell their post-distillation litter as a domestic landscaping mulch.
• Factoring in transport and spreading costs, mulch is generally significantly more extensive than herbicide application. Growers choosing this approach would also be foregoing the opportunity to sell their tea tree harvest by-product as a landscape mulch product.

7.6.2. Farm hygiene

Effective farm hygiene restricts the spread of weed seeds and reproductive plant parts (propagules) from one location to another. This can include weed spread from farm to farm, as well as weed spread within the farm. Relevant activities are commonly referred to in tea tree production and other cropping systems as preventive weed control.

Some general principles for farm biosecurity and hygiene on tea tree plantations include (see also Virtue 1999, Kristiansen et al. 2014b, Ross & Fillols 2017, Plant Health Australia n.d.):

• Establish new crops on a site that has a good history of weed management if possible, including effective management during site preparation (see Section 7.2).
• Ensure new crop seedlings are certified weed-free if possible.
• Monitor the crop for outbreaks of new weed species regularly, and control these as soon as identified before they have a chance to spread. Map these sites to make them easy to monitor over time. Avoid activities that may spread weed seed from the outbreak sites, such as limiting flood irrigation or cultivation on the site.
• Have biosecurity signage on the farm to make visitors and contractors aware of the risk. Restrict unnecessary movement onto the farm as much as possible.
• Ensuring contractor and visitor machinery, vehicles and footwear are as clean as possible of weed seed.
• Ensure weeds in adjacent non-cropping areas (e.g., fence lines, sheds and infrastructure, laneway verges) are managed.
• Establish set vehicle tracks or laneways.
• Where livestock are used to graze the tea tree crop for weed control, place them in quarantine for two weeks prior to grazing, to ensure all viable weed seed have passed through their gut. Monitor the quarantine site subsequently for unusual weed species.

7.6.3. Grazing

Grazing may be effective within more mature plantations, resulting in minimal crop damage given that tea tree is not palatable to livestock. Its short-term benefits can be expected to be similar to mowing, particularly if stocking rates/grazing intensity are high (Virtue 1999), however livestock are considered to have some benefit in controlling the type of woody perennial weed species favoured by tea tree production systems, particularly in their seedling stage (Corteva Agriscience 2019). Effectiveness of the technique can be maximised by using electric fences to establish intensive grazing cells at high stocking rates for relatively short periods of time. More effective weed control will result, with less damage to the crop (Colton et al. 2000).
Sheep tend to be more effective than cattle in grazing for weed control, as they are less likely to damage the tea tree crop, graze closer to the ground, and are less selective eaters meaning they graze a higher proportion of weeds present. However, the warm humid climates characterising coastal tea tree production zones in Australia, as well as frequent waterlogging, tend to be less suitable to sheep than cattle due to the greater risk of illness and disease (Virtue 1999, Colton et al. 2000).

A tea tree industry survey found grazing (with cattle) was rated relatively poorly, and less effective than herbicides and cultivation. In the longer-term, selective grazing of palatable species by cattle may leave unpalatable (though still competitive) weed species in the crop (Sutton et al. 1997).

### 7.6.3.1. Advantages and disadvantages

One of the attractions of grazing as a weed control approach in tea tree plantations is the opportunity to offset the cost of weed control somewhat through livestock breeding and sales (Virtue 1999). Nonetheless, producers who decide to graze for weed control within a tea tree plantation will not only require sufficient knowledge of livestock management principles such as rotational grazing, breeding and fattening, but also willingness to dedicate sufficient time to livestock maintenance, and to invest in infrastructure such as suitable fencing, holding and working yards (Sindel & Coleman 2012), veterinary medicine and potentially veterinary support. Some of these costs and management issues, including the cost of purchasing livestock, may be mitigated if it is possible to come up with a share farming or agistment arrangement with a neighbouring grazier (Bekkers 2011).

Another potential drawback of grazing is that in wet conditions, grazing animals can contribute to soil compaction and potentially ponding of water, reducing crop performance (Private Forests Tasmania 2017). Grazing animals may also contribute to the spread of weeds across tea tree plantations, by eating weed seed which remains viable after passing through their digestive system (Vasic et al. 2012).

### 7.6.3.2. Principles from grazing in viticulture

In the Australian and New Zealand wine industries (Madge 2007, Bekkers 2011, Penfold & Collins 2012), sheep grazing over the winter fallow period has been found to be beneficial in managing weeds within vineyards outside the vine growing season. Little damage is done to the vines, and small amounts of infrastructure damage arising from grazing was considered acceptable. This suggests that more intensive grazing in the period immediately following harvest may be appropriate in tea tree plantations to ‘clean up’ weeds that were present beneath the crop canopy, and before regrowth commences. However, practical limitations may include availability of adjacent grazing land for near-year-long grazing rotation.

### 7.6.4. Perennial cover crops

Cover crops have been suggested for their potential to suppress weeds in tea tree plantations, with living cover crops found to be relatively effective at suppressing weeds in orchard production (Tursun et al. 2018). Constantly maintaining bare ground in a plantation naturally exposes the producer to constant weed incursion (Madge 2007). However as an alternative to bare ground, cover crops can reduce weed pressure by competing for light, nutrients and soil moisture (Barney & Finnerty n.d.). In some other tree crop systems in Australia, semi-permanent cover crop grass/legume swards such as white clover/perennial ryegrass/fescue are fairly commonly used in inter-row spaces (Harrington 2000). Total weed control both in the crop rows and the inter-row space in other crops such as orchards has given way to ground cover maintenance between the rows, considered more environmentally sustainable than inter-row cultivation and/or herbicides (Perennia 2013).
7.6.4.1. Establishment

Perennial cover crops may be as useful in the inter-row space of tea tree plantations, with replenishment of the cover crop seed bank every summer, and re-sowing taking place every few years. The best time to establish a cover crop in tea tree plantations will be either during crop establishment or after crop harvest, and after weed management activity (herbicide, cultivation) has been completed, to commence with a clean space and maximise the early competitiveness of the cover crop. Establishing the cover crop during crop establishment is the preferred approach, planting across the entire site and then spraying out the crop planting lines with a non-selective herbicide before planting, however modified commercial disc seeding equipment can be used to sow cover crops in the inter-row space of tea tree crops (Colton et al. 2000, Harrington 2000, Unknown 2009, Rose et al. 2019). A cover crop mix of annual grasses and perennial legumes may be considered, with the slower-growing perennial species taking over after the annual species dies (Evans et al. 1988).

7.6.4.2. Management and integration

Any cover crop would need to be managed very closely (e.g. by mowing) to keep the sward under control and avoid it becoming overly competitive with the crop. Mowing cover crops has also been found to decrease weed species richness and weed density in orchard production (Tursun et al. 2018). Weed control is likely to be needed within the cover crop during the early stages of its establishment, particularly if a slower-growing prostrate perennial species is used (Evans et al. 1988). A ‘side-discharge’ mower may be used to deliver the mown cover crop residue into the crop rows and form a mulch layer (Barney & Finnerty n.d.), however this is likely to be counter-productive from the weed management standpoint if weeds that have gone to seed are present within the cover crop.

Utilising a perennial rather than annual inter-row cover crop sward would preclude the need to cultivate/spray the inter-row space to re-establish an inter-row cover crop each year, reducing costs and helping to maintain both soil and crop health (Colton et al. 2000, Harrington 2000, Unknown 2009). Some other benefits may include improving soil quality, reducing erosion, and providing a more reliable trafficable surface in wet conditions (Barney & Finnerty n.d.).

Inter-row cover cropping may work well with grazing as part of an integrated approach, however even a mown or grazed cover crop could still provide significant competition with the tea tree plantation, potentially reducing crop yield significantly (see Section 6.2). In other tree crop and viticultural systems in Australia, some growers appear to accept some reduction in yield in order to obtain the benefits of inter-row ground cover (Harrington 2000).

7.6.4.3. Limitations

The ‘ideal’ specific requirements of a cover crop in the tea tree plantation context can be difficult to meet from amongst available types. These include: rapid establishment, prostrate growth habit, perenniality, shallow rootedness, limited competition with the crop for nutrients, limited to no allelopathic effect on the tea tree crop, reducing soil temperature during the hottest parts of the year, and ability to persist in shade and waterlogged soils (Virtue 1999, Barney & Finnerty n.d.).

Focusing on prostrate and semi-prostrate legume species, Virtue (1999) considered that no species met all of these requirements satisfactorily, so some compromise would inevitably be required. Perennial legumes may provide soil nitrogen for the crop, but will still compete with the crop for moisture, potentially reducing tea tree yield (Colton et al. 2000).

The capacity of perennial legumes to enrich the soil through nitrates can also eventually allow grassy weed competitors to take advantage of improved soil quality, and out-compete the cover crop if it is not sufficiently vigorous (Duncan 2017). Faced with overwhelming weed pressure within the cover crop, or undesirable cover crop impact on tea tree crop growth, it may be necessary to terminate an inter-row cover crop (Rose et al. 2019). This suggests that some shielded inter-row herbicide use is still likely to
be required. The range of selective herbicide options available to the producer are most likely to decrease markedly where the goal is to maintain the cover crop without herbicide damage.

7.6.5. Site management and crop competitiveness

Decisions taken in selecting, establishing and maintaining a plantation site and the subsequent crop, can have implications for tea tree’s competitiveness against weeds (Virtue 1999, Colton et al. 2000, Prastyono 2008, Baker.G.R et al. 2010, UC IPM 2017):

- **Site drainage**: in tea tree plantations, long periods of waterlogging (e.g. after a flood event or heavy rainfall) can favour establishment of difficult to control ‘water-loving’ rushes and sedges, and may also reduce the effectiveness of herbicides by increasing their rate of dissipation. *Laser-levelling* the site prior to establishment of a plantation can facilitate quicker site drainage following inundation, and not only reduce the incidence of competitive weed species but allow more timely machinery access to the paddock for all weed control activity.

- **Harvest time**: the ideal time to harvest tea tree is late spring-summer (in NSW). This provides the warm temperatures needed immediately after harvest for the coppiced trees to reshoot rapidly. Thus, tea tree plants will be less likely to be outcompeted by weeds early post-harvest weeds and will form a canopy sooner to shade the inter-row space. Harvesting in cooler weather may result in a longer crop re-establishment period, increasing the risk that weeds will become more competitive and reduce the yield of the subsequent crop.

- **Tree size at harvest**: larger trees at harvest can regrow more quickly because of their higher root/shoot ratio. Encouraging a deep, vigorous root system during crop establishment will facilitate rapid regrowth each season and maximise the capacity of tea tree to out-compete weeds.

- **Plant competitiveness**: breeding programmes have been underway since 1993, to improve the yield and performance of tea tree varieties suitable for commercial plantations. Using improved varieties which are likely to establish and grow at a faster rate, as well as recover more quickly post-harvest, can help maximise tea tree’s capacity to out-compete weeds in the field.

- **Plantation layout and planting density**: closely spaced and straight planting rows provide several advantages from the weed management perspective.
  - By maximising yield (and profit) per hectare, more funds are available to use on crop and weed management.
  - Close row spacings facilitate a dense canopy which is more likely to out-compete weeds for resources.
  - Appropriate spacing and straight rows make it possible to access the crop easily for herbicide application, cultivation or mulch application using standard row crop machinery. A spacing of 1 metre between rows is commonplace, to maximise full ground cover after harvest.
  - A planting density of 35,000 trees/ha is considered ideal to meet the dual goals of maximal weed suppression and crop yield.

- **Nitrogen supply**: maintaining sufficient nitrogen nutrition for the crop and applying it preferentially to crop trees rather than weeds, will help maximise crop competitiveness with weeds.

- **High water table**: reducing moisture competition between the crop and weeds, and maximising crop growth and regrowth rate, means selecting a site with a high water table for crop establishment.

- **Effective insect management** will also maximise the crop’s growth and therefore competitiveness with weeds, particularly important during the early regrowth stage of the crop.

7.7. Integrated Weed Management

Integrated Weed Management (IWM) involves combining all appropriate weed control options in a coordinated and flexible way to minimise the impact of weeds (Sindel 2000).

Relying on one or two tried and true methods alone (such as herbicides) is less likely to succeed in the longer term. It will eventually result in increased populations of certain weeds (‘selection pressure’), or
an increase in weeds that are difficult to control (for example through reduced herbicide effectiveness, or herbicide resistance).

Integrating a range of approaches and timing them appropriately so that they support each other will reduce selection pressure, and make it less likely that particular weed species will come to dominate the plantation (Storkey & Neve 2018). ‘Timing’ also involves managing weeds wherever possible before they have had a chance to produce seed, therefore reducing the weed seed bank and the future weed problem (Madge 2007).

Virtue (1999, p. 93) provides a succinct summary of the importance of IWM in tea tree plantations (emphasis added): All weed control techniques have advantages and disadvantages in their use regarding extent of weed kill, relative cost, effect on soil health, tree damage, skills required and suitability in wet conditions. Weed kill should be maximised at minimum cost for greatest profit, but with long-term soil health in mind. A single technique cannot be solely relied upon as it will inevitably select for weeds that are tolerant to the technique. Rather, different techniques should be integrated within and between years, considering the stage of the regrowth cycle, weather conditions and the risk of yield loss due to weed competition.
8. Knowledge and research gaps

8.1. Gaps related to the impact of weeds

This literature review suggests a lack of information in a range of areas regarding the impact of weeds within tea tree plantations in Australia. Several research questions may be considered and prioritised based on industry need and available research funds:

- What is the farm-level economic impact of weeds on TTO production, but in terms of the cost of weed management and their impact on oil yield and quality?
- Do any of the key weeds of the industry have an allelopathic effect on tea tree?
- Do any of the key weeds of the industry host insects or diseases that have a negative impact on crop productivity?
- Can weed contamination of harvested biomass be shown to impact negatively on the quality of resulting tea tree oil?

Understanding the impact of weeds in tea tree plantations can help to place weeds appropriately in the spectrum of management problems faced by TTO producers and help motivate ongoing research efforts to reduce this impact.

8.2. Gaps related to weed management practices

In this section, possible opportunities to expand the range of weed management options available in tea tree production are summarised. We also include details of weed management approaches currently used in other tree crops (as well as broadacre cropping and vegetable production), which may warrant further exploration for their relevance in tea tree plantations. Some may already be in limited use in tea tree production, but this was not evident during literature search.

8.2.1. Alternative herbicides?

Summary: flumioxazin is likely to become available to tea tree producers soon as a post-harvest and post-emergent product. Further industry consultation may confirm the suitability and current trial status of quizalofop-p-ethyl, sethoxydim and a haloxyfop/clethodim tank mix, and potentially identify other suitable herbicides for future screening research.

McMillan and Cook (1994) evaluated 65 herbicides for their effectiveness in tea tree crops. Of the herbicides screened, the options listed below in Table 5.2 were recommended to the industry. The report should be referred to for specific details on the results relating to each product recommended. Herbicides that appear to have been discontinued, or not currently registered in Australia for any situation, are not included in the Table 5.2.
Table 5.2  
**Herbicides recommended by McMillan and Cook (1994), and their current registration status for tea tree**

<table>
<thead>
<tr>
<th>Recommended stage</th>
<th>Crop growth stage</th>
<th>Herbicide active ingredient</th>
<th>Herbicide group</th>
<th>Current status in tea tree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-plant, pre-emergence</td>
<td>Oryzalin</td>
<td>D</td>
<td>Full registration</td>
<td></td>
</tr>
<tr>
<td>Pre-plant, pre-emergence</td>
<td>Metolachlor</td>
<td>K</td>
<td>Minor use permit</td>
<td></td>
</tr>
<tr>
<td>Pre-plant, pre-emergence</td>
<td>Simazine</td>
<td>C</td>
<td>Minor use permit</td>
<td></td>
</tr>
<tr>
<td>Pre-plant, pre-emergence</td>
<td>Trifluralin</td>
<td>D</td>
<td>Minor use permit</td>
<td></td>
</tr>
<tr>
<td>Post-plant, pre-emergence</td>
<td>Metolachlor</td>
<td>K</td>
<td>Minor use permit</td>
<td></td>
</tr>
<tr>
<td>Post-plant, pre-emergence</td>
<td>Oryzalin</td>
<td>D</td>
<td>Full registration</td>
<td></td>
</tr>
<tr>
<td>Post-plant, post-emergence</td>
<td>2,2-DPA</td>
<td>J</td>
<td>Full registration</td>
<td></td>
</tr>
<tr>
<td>Post-plant, post-emergence</td>
<td>Acifluorfen</td>
<td>G</td>
<td>Not registered or permitted</td>
<td></td>
</tr>
<tr>
<td>Post-plant, post-emergence</td>
<td>Clopyralid</td>
<td>I</td>
<td>Minor use permit</td>
<td></td>
</tr>
<tr>
<td>Post-plant, post-emergence</td>
<td>Flupropanate</td>
<td>J</td>
<td>Minor use permit</td>
<td></td>
</tr>
<tr>
<td>Post-plant, post-emergence</td>
<td>Methabenzthiazuron</td>
<td>C</td>
<td>Not registered or permitted</td>
<td></td>
</tr>
<tr>
<td>Post-plant, post-emergence</td>
<td>Fluazifop-p-butyl</td>
<td>A</td>
<td>Full registration</td>
<td></td>
</tr>
<tr>
<td>Post-plant, post-emergence</td>
<td>Haloxyfop</td>
<td>A</td>
<td>Minor use permit</td>
<td></td>
</tr>
<tr>
<td>Post-plant, post-emergence</td>
<td>Quinalofop-p-ethyl</td>
<td>A</td>
<td>Not registered or permitted</td>
<td></td>
</tr>
<tr>
<td>Post-plant, post-emergence</td>
<td>Sethoxydim</td>
<td>A</td>
<td>Not registered or permitted</td>
<td></td>
</tr>
<tr>
<td>Post-harvest</td>
<td>Simazine + paraquat</td>
<td>A + L</td>
<td>Tank mix</td>
<td></td>
</tr>
<tr>
<td>Post-harvest</td>
<td>Paraquat/diquat</td>
<td>L</td>
<td>Full registration</td>
<td></td>
</tr>
</tbody>
</table>

Entwistle (2013) noted that the herbicide methabenzthiazuron had ‘some potential’ for post-emergence selective broadleaf and sedge weed control in tea tree plantations. This product had previously been available to TTO producers under a minor use permit (expiring in 2006), however at the time of writing was not available to TTO producers either via a minor use permit or full registration. Further trial work was undertaken, with similar results obtained to the currently available herbicide clopyralid. As a result, registration or minor use permit application has not been pursued (Entwistle 2020).

When trialled as selective broadleaf herbicides, bentazon and bromoxynil were found to be relatively ineffective, and not worth consideration for future trial activity. Similarly, oxyfluorfen and acifluorfen were found to result in unacceptable levels of phytotoxicity when trialled as selective broadleaf herbicides, while imazethapyr caused longer-term crop stunting when trialled through directed shielded application (Entwistle 2013). Oxyfluorfen is currently available under the minor use permit as a pre-emergence option (Table 5.1).

Two herbicides listed in Table 5.2 not currently available to producers either via a minor use permit or full registration (and not subject to more recent trial activity) may warrant considering once again, potentially with revised field trials to re-evaluate their suitability: quinalofop-p-ethyl (e.g. Quinalofop-P-Ethyl 200); and sethoxydim (e.g. Cheetah Gold). Both are registered for use in other crops to manage grass weed species.
More recently, the Group G herbicide flumioxazin (Chateau®) has been trialled as an over the top selective as well as pre-emergent herbicide with some success in tea tree plantations, applied at approximately 3x the recommended rate with no noticeable side-effects on the crop. At the time of writing, residue testing was underway, with some questions still to be addressed regarding phytotoxicity on tea tree when applied to post-emergent coppice where another herbicide has already been used. However providing the results of this testing are satisfactory, ATTIA will most likely apply for a minor use permit for this herbicide: post-emergent over tea tree seedlings, and post-harvest prior to coppicing via shielded application (Larkman 2019, Entwhistle 2020).

Other recent industry trials (Unknown 2018, Entwhistle 2020) indicated that a mix of haloxyfop at 400ml/ha, clethodim at 500ml/ha and the penetrant Pulse at 200ml/100L water provided promising control of smaller weeds in particular, while older grasses were suppressed only. No chemical residues were found in tea tree leaf samples collected 7 days after application.

Further work was required to determine the limitations of this mix against weeds of different size and life stage. Haloxyfop is currently available to TTO producers, though clethodim is not available for use under full registration or minor use permit.

### 8.2.2. Herbicide resistance

**Summary:** What is the extent of herbicide resistance in the tea tree industry, particularly in relationship to the most significant weed species and registered/permitted herbicides? How can resistant weed populations be managed to mitigate this risk to the industry?

Herbicide resistance is strongly suspected in the tea tree industry (Entwhistle 2020). However, no evidence of resistance testing specific to this industry was identified in the literature and may be a future research priority.

A detailed review of herbicide resistance literature falls outside the scope of this project, nonetheless, some examples of herbicide resistance have been identified elsewhere over the course of this review, involving weed/herbicide combinations relevant to TTO production:

- Linuron-resistant populations of annual ragweed (*Ambrosia artemisiifolia*) have been identified in carrot production in Canada (Simard et al. 2018).
- Paraquat-resistant populations of Colombian waxweed (*Cuphea carthagenensis*) have been identified in Fiji (CABI International 2015).
- Atrazine- and trifluralin-resistant populations of *Setaria* spp. in France and Canada (Darmency et al. 2017).
- Glyphosate-resistant populations of milk thistle (*Sonchus oleraceus*) in broadacre cropping in Australia (van der Meulen et al. 2016).
- Glyphosate-resistant populations of fleabane (*Conyza* spp.) in broadacre cropping in Australia (Charles 2013).
- Atrazine-resistant populations of blackberry nightshade (*Solanum nigrum*) in pea crops in New Zealand (Harrington et al. 2001).

A full herbicide resistance study may require:

- Identifying all relevant examples from Australian and overseas literature (building on the preliminary list provided above.
- Conducting an industry survey to determine the extent of suspected herbicide resistance and/or reduced effectiveness (location, weed species, herbicide).
- Testing identified populations and herbicides in laboratory and field conditions.
The preliminary search conducted here indicates that TTO producers are at significant risk of herbicide-resistant weed populations taking hold in tea tree plantations – if they have not already done so. Awareness of the extent of resistance will help the industry (and particularly growers working plantations where resistance has been shown to exist) to identify and then utilise alternative strategies to manage any resistant populations, perhaps specific to the weed species in question.

### 8.2.3. Stale and false seed beds

**Summary:** stale and false seed beds are likely to help TTO producers to reduce the weed seed bank during crop establishment, but their potential usefulness within an established crop is likely to require field evaluation.

*Stale seed beds* involve preparing a seed bed up to several weeks before crop planting, and then leaving the bed undisturbed before planting. In this period, weeds are allowed to germinate and their growth possibly stimulated through irrigation, and then controlled before they have produced seed with a non-selective herbicide just before the crop is planted (Lonsbary et al. 2003). The goal is to gradually reduce the weed seed bank in the paddock.

*False seed beds* are similar, but involve repeated shallow cultivations or non-selective herbicide applications to prepared crop beds over several weeks before planting or sowing (DAFF 2010, DAFF 2013). In other industries such as vegetable production, it is relatively common to use a mix of shallow cultivation non-selective herbicides or flaming, depending on available equipment and time.

It is unclear from the literature the extent to which these options are currently used by the industry on new plantation sites. Nonetheless, stale and false seed beds could be a relevant addition to pre-plant weed control on new plantation sites, following on from deeper cultivation which is used to prepare the ground for planting (see Section 7.5.1). They are unlikely to be applicable once the crop is established. However, assuming few to no mature perennial weeds are present in the inter-row space, an inter-row stale or false seed bed using a non-selective herbicide or shallow ‘tickle’ cultivation may be relevant soon after harvest to help reduce the weed seed bank.

### 8.2.4. Killed mulches and strip tillage during crop establishment

**Summary:** establishing a new tea tree crop within a killed mulch may help to retain soil moisture and structure in the early days of the crop and provide some competition for weeds. It would be possible to use herbicides over the top of the killed mulch to control weeds, however the benefits of the killed mulch layer would only be short-term as the cover biomass breaks down. Field trials may identify the potential benefits of this technique for weed and soil management.

*Strip tillage* is unlikely to be relevant to tea tree plantations, given: its potential to reduce crop yield through competition; ongoing management requirements of the inter-row green strip being identical to that of a perennial cover crop; and because its ongoing presence would preclude options such as shielded inter-row or selective herbicide application which may damage the cover crop layer.

‘Killed mulches’ involve planting a cover crop that is subsequently killed using a non-selective herbicide, with the crop being planted into the resulting ‘mulch’. In tea tree plantations, this approach has some potential to be used as a follow up to other crop bed preparation activity (Section 7.2) to allow new tea tree crops to establish with significantly less early-stage weed competition (Harrington 2000).

Killed mulch relevance in tea tree may be reduced by the limited time present of the resulting mulch layer following cover crop termination, with biomass break-down several weeks to months later possibly allowing weed cohorts to emerge. However, these could then be controlled over the top of the killed mulch layer using ‘standard’ tea tree practices such as shielded inter-row and/or selective herbicides (Section 7.4). The killed mulch layer may assist in tea tree crop establishment and competitiveness with weeds during the vital early post-transplant stage, in addition to providing soil...
nutrient benefits. Growers would need to factor in the time and expense required to sow, and maintain a cover crop, and terminate it a killed mulch.

Similarly, ‘strip-tillage’ (Brainard et al. 2013) may be considered. This technique involves cultivating only a narrow strip within a cover crop prior to seedling transplanting, such that the cover crop suppresses most weeds. Nonetheless, the potential of the cover crop selected for either strip tillage or a killed mulch to out-compete or reduce the rate of tea tree growth during its establishment phase (due to competition for resources) would need to be taken into account (Section 7.2).

### 8.2.5. Synthetic mulch films during crop establishment

*Summary: synthetic mulch films are unlikely to be suited to tea tree plantations.*

Synthetic mulches (or weed mats) are expensive to purchase. Application can be time-consuming and requires specialised equipment. Their use in other industries such as vegetables and fruit are generally to be restricted to high-value crops such as cucurbits, strawberries and tomatoes. They have also been trialled in perennial row crops such as lavender. Furthermore, despite their effectiveness in stopping most weeds from growing, they still may not suppress some perennial weeds or sedges found in tea tree crops (such as nutgrass, *C. rotundus*), as these are known to be capable of piercing the plastic mulch layer (Henderson & Bishop 2000, Sindel et al. 2012, Westerveld 2013, Kristiansen et al. 2014a).

In the tea tree industry, plastic mulches and weed matting use tends to be restricted to tea tree nurseries, where the value and limited time in situ of the plants warrants using a product that will lose its effectiveness after a few months as it deteriorates (Virtue 1999, Harrington 2000, ATTIA 2018, Larkman 2019).

Because plastic mulches are only a short- to medium-term solution for weed suppression, they will not be feasible in perennial tea tree production, even in establishment of a new plantation (Sindel et al. 2012, Kristiansen et al. 2014a):

- The cost and time involved in plastic mulch removal is significantly greater in vegetable production systems where weeds or crop residues attach to the mulch layer, and this is likely to be an even greater issue in a tea tree rows where the crop remains in place, and the mulch layer would need to be removed around established trees.
- Application of plastic mulches in vegetable production requires a uniform, smoothly formed bed. The row formation typical of tea tree plantations may not suit plastic mulch application.
- Leaving a plastic mulch in situ in a tea tree crop is not viable, as the mulch layer will eventually break down and create a significant environmental (litter) problem.
- If an original plastic mulch film were removed, it would not be possible to replace it. Other more conventional weed control would need to replace the mulch.

### 8.2.6. Biodegradable mulch films during crop establishment

*Summary: biodegradable mulch films may offer TTO producers an extra tool in suppressing weeds from plantation establishment through to first harvest. However, their performance and cost-effectiveness vs 'standard' crop establishment practices needs to be evaluated in the field.*

TTO producers establishing a new plantation may consider using a biodegradable mulch film to help suppress weeds. These are designed to last for several months after laying, so that they maintain sufficient weed control and moisture retention during the life of the crop, but degrade to the extent that they may be cultivated into the field post-harvest, leaving no toxic residues in the soil (Heisswolf & Wright 2010, Limpus 2012, Razza & Degli Innocenti 2012).

Ongoing trials in Australia and overseas suggest that biodegradable mulch performance is improving, and they are becoming more cost-effective. However a range of issues may also make biodegradable

- Potentially much greater cost, in contrast to standard field preparation and early post-plant weed management.
- Uncertain life span in waterlogged situations.
- Tendency of the film to be easily pierced and damaged (thereby exposing the ground to weed germination).
- Susceptibility to penetration by woody perennial species and sedges.
- Litter issues still potentially relevant to some biodegradable products, particularly as the product is breaking down into large pieces.

There may be a research opportunity to contrast biodegradable mulch performance with standard industry practices for weed management in a planted and establishing tea tree crop. Such a project should include an economic component to contrast the relative costs and benefits of the two options.

### 8.2.7. Crop row orientation

*Summary:* east-west crop orientation shows promising signs for improving crop competitiveness with weeds in other crops. It may offer similar assistance in tea tree, though field trials would be required to explore crop-weed and crop-crop competition factors, comparative crop yields, and comparative weed burdens. Such orientation would also need to suit the physical characteristics of each site.

As discussed in Section 7.6.5, maximising crop planting density can reduce the impact of weeds through greater competitiveness of the crop.

However, no information was identified in the literature on whether adjusting *crop row orientation* (row axis relative to the compass) has any relationship to weed impact in tea tree plantations.

In other crops this weed management technique also appears to be in exploratory stages, but it shows some promise, particularly when combined with relatively narrow row spacing and higher planting density. For example, research in wheat production indicates that crop rows oriented on an east-west axis (that is, at right angles to the direction of the sun) may suppress weed growth in the inter-row space through more effective shading, particularly when combined with closer row spacing (Borger et al. 2010, Hozayn et al. 2012, Cook et al. 2015, Borger et al. 2016).

Likewise, orienting tea tree crop rows on an east-west axis may help tea tree crops to out-compete weeds during the annual regrowth stage, potentially increasing yield at harvest. However, during initial crop establishment and immediately following harvest, the minimal to no shading provided by the crop would not be a factor in weed competitiveness, and other weed control practices would remain necessary.

Field trials would be required to assess the benefits of an east-west crop orientation in relation to north-south or other orientations, not only from the weed management point of view but also crop performance, harvest biomass and oil yield. If beneficial, this option may be considered by producers as they establish new plantations or replace older plantations. On some plantation sites, there may be little flexibility to select from crop orientation options, depending on factors such as land slope and drainage, water access sources and locations, other infrastructure location, and property dimensions.

### 8.2.8. Weed identification, scouting and mapping

*Summary:* understanding the ecology, behaviour and locations of important weeds within tea tree plantations may assist TTO producers to ensure control activity is tailored appropriately to these species. Information on behaviour and effective management of important weeds may be required to allow targeted control.
In the blueberry industry (Agriculture Acquaculture and Fisheries New Brunswick 2017, Miller n.d.) producers are recommended to be able to identify the main weeds present in their crop at different times of year, and understand key aspects of their ecology and biology, such as perenniality and form/s of reproduction. For example:

- Annual weeds are likely to grow rapidly and produce large quantities of seed. Control activity may focus on reducing the possibility of weeds producing seed, particularly in the case of flowering plants.
- Perennial weeds will produce extensive root systems. Control is likely to be difficult for more mature plants, and particularly so for species which spread via underground rhizome networks.

This information could also help producers to decide which management techniques are most likely to contribute to successful IWM in tea tree plantations, and which are less likely to be effective (see also Chapter 9). For example, some available herbicides may be more effective in managing the weeds present than others. The mix of techniques used may need to adjust where weed populations and dominant weed species change across the plantation over time.

‘Weed scouting and mapping’ may be appropriate to keep track of weed spread and control trends, and may be particularly helpful in: addressing outbreaks of new weed species on a site before they become dominant; identifying and recording weed ‘hotspots’ within a plantation; and evaluating the effectiveness of weed control methods that have been implemented (Madge 2007, Agriculture Acquaculture and Fisheries New Brunswick 2017, UC IPM 2017, Lanini & Grant n.d., Miller n.d.).

8.2.9. Thermal weed control in establishing and established plantations

Summary: saturated steam weeding is already showing promising results in Australian TTO production and may offer an alternative to herbicides for safe control of recently germinated weeds in particular in tea tree plantations. Possible limitations and relevance to control of mature and perennial weeds require further trial. Flame weeding is unlikely to be suitable.

Flame weeding involves using natural gas- or propane-fuelled burners to expose weeds to sufficient heat to destroy weeds. In vegetable production it tends to be used as an alternative for non-selective herbicides, and may find a similar use in tea tree (Henderson & Bishop 2000). Flame weeding implements tend to be hand operated, either wheeled or hand-held with the fuel supply mounted on a tractor, backpack or trolley. Hooded flaming implements are also available. In tea tree plantations, flame weeding has been found to be most effective immediately following harvest. However, it effectiveness varies amongst weed populations (Colton et al. 2000). In other perennial crops, burning may be used to manage weeds as part of site preparation activity, however it is considered to stimulate a broader spectrum and density of weeds (Private Forests Tasmania 2017).

Soil steaming (‘steaming’) has the potential to be very effective for control of weeds in vegetable crops (Melander et al. 2005). As with soil solarisation, steaming has several benefits for soil and crop health other than for weed management, by allowing some control of bacteria, viruses, fungi, and nematodes that can harm the crop.

There are a range of steaming options available, including:

- **Surface-level steaming** wands, connected to a steam generator, to kill surface-level plants (hooded and non-hooded options available).
- **Saturated steam weeding**, ‘superheating’ water to deliver saturated steam onto the soil surface via hooded wands or tractor-mounted implements (Weedtechnics n.d.).
- **Soil thermal weeding** (Merfield 2016) which involves injecting steam into the top layer of sheeted/covered soil to destroy weed seed beneath the surface.
Saturated steam weeding is already being trialled in the Australian tea tree industry, with promising results (Winer 2019). Further research may be useful in comparing saturated steam weeding in established tea tree plantations with more conventional approaches such as herbicide use, from both weed suppression and economic perspectives. Its performance against larger and particularly woody perennial species will also require evaluation, as it is most likely to be suited to controlling recently germinated weeds (Melander et al. 2005).

Both flame and steam weeding have important limitations, including relative ineffectiveness against grass weeds, the need for several treatments, high fossil fuel use, and low work rates (Kristiansen & Smithson 2008, Bekkers 2011, Kristiansen et al. 2014b). Small annual weeds will be relatively easy to kill using flame weeding, whereas perennial and larger annual weeds are likely to re-establish after approximately two weeks. Over time, perennials (especially those with persistent underground reproductive parts) will become dominant where flame weeding is relied on heavily (Colton et al. 2000). Flame weeding would also pose a fire risk where crop rows have been treated with tea tree litter mulch.

8.2.10.Robotics and automation in establishing and established plantations

**Summary:** robotic weeding systems is a relatively new technology which continues to advance rapidly. Robotic weed management has considerable potential in TTO production, though field trials and economic evaluation should be undertaken, particularly given the relatively small scale of many tea tree operations.

Automated detection and control using remote sensing equipment has been under development for over a decade for use in broadacre, vegetable and tree crop situations. Technology is being developed to differentiate weeds from crop plants, or weeds from bare ground. Control options using robotics include using shallow cultivation, targeted or direct herbicide application, or even chipping (van der Weide et al. 2008, Fulwood 2019). UAV/drone-mounted technology is also under development to detect and then control woody weeds from the air using targeted herbicide application (Unknown 2014).

Automated weeding has a range of potential advantages in tea tree production, including:

- Providing an alternative to expensive weed management tactics such as hand weeding and cultivation.
- Reduced herbicide costs through targeted rather than broad-scale herbicide application.
- Using herbicides in a targeted fashion at full rates to maximise the chance of successful weed management, rather than more cost-effective lower rates on a broad scale.
- Being able to work continuously (or until battery re-charge).
- Being able to operate autonomously and systematically, without need for human intervention.
- Given their relative lightness compared to a tractor with spray rig, field robotic systems have the potential to get onto the paddock sooner after flooding, heavy rainfall or irrigation, managing weeds before they become larger and more problematic. This can also be of benefit by reducing soil compaction between the crop rows.
- Helping to address the issue of herbicide resistance, by allowing for targeted control of herbicide-resistant weed species relatively early in their life cycle.

9. Extension needs

Other cropping industries in Australia have access to detailed Integrated Weed Management (IWM) guidelines in written form (Cotton Research and Development Corporation 2014, Storrie 2014, Ross & Fillols 2017), and some of the general principles covered in these documents will have some relevance to tea tree production. Written best practice management guides for weed management are a popular
resource for rural landholders, and are particularly beneficial when used in support of face-to-face extension activity such as industry development farm visits and field days (Coleman et al. 2017).

Ultimately, IWM guidelines for tea tree plantations would benefit the industry by incorporating herbicides and other weed management techniques in a sustainable approach. To develop IWM guidelines for Australian TTO production, current weed management practices, their limitations, and the extent of weed problems need to be far better understood to underpin recommendations with factually based data.

Given the relatively small scale of the Australian tea tree industry and lack of industry-specific development officers at the time of writing, it may be preferable to produce a ‘integrated pest management’ guide, or crop production guide, of which weed management may form one aspect.

Colton et al. (2000) appears to be the most recent example of such materials available to the industry and includes a relatively extensive section on weed management in tea tree plantations. Depending on access to crop production and protection information by TTO producers (e.g. through the ATTIA newsletter and annual meeting), it is potentially valuable to update this publication to take current practices, potential innovations and major issues faced into account across all aspects of tea tree crop management.

Bright (2018) represents a more recent example of a crop protection guide, in this case produced for the macadamia industry in NSW, though primarily with a non-weed pest focus.

The current project may assist in identifying the most significant weeds to the TTO industry in Australia (see also Table 5.1). Producers may benefit from detailed management guides specific to these ‘priority weeds’, drawing on general ecology and management information sources (e.g. CABI International 2015) and management information from other cropping industries, but repackaged in a way to ensure information is relevant to TTO production.
10. References


AgriFutures Australia. n.d. Tea tree oil industry: 25 years. AgriFutures Australia, Wagga Wagga.


Entwistle, P. 2013 Improving the Sustainability of Plant Protection in Tea Tree Oil Production Systems. Rural Industries Research and Development Corporation, Barton.


Kawate, M.K. and Tarutani, C.M. 2006 *Pest Management Strategic Plan for Macadamia Nut Production in Hawai‘i*. Pearl City Urban Garden Center, University of Hawai‘i at Manoa, Honolulu.


O’Hare, P. 2004 *Macadamia grower’s handbook*. Department of Primary Industries and Fisheries, Nambour.


Scoping study of sustainable weed management in tea tree oil plantations
Appendix 1: Review of Literature

by Michael Coleman, Paul Kristiansen, Christine Fyfe and Brian Sindel
November 2020

AgriFutures Australia Publication No. 20-129
AgriFutures Australia Project No. PRJ-011789


---

AgriFutures Australia
Building 007
Tooma Way
Charles Sturt University
Locked Bag 588
Wagga Wagga NSW 2650

02 6923 6900
info@agrifutures.com.au

@AgriFuturesAU
agrifutures.com.au

AgriFutures Australia is the trading name for Rural Industries Research & Development Corporation. AgriFutures is a trade mark owned by Rural Industries Research & Development Corporation.