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A survey of herbicide use and a review of environmental fate in New Zealand planted forests

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Abstract

Background: This paper examines current herbicide use in New Zealand planted forests. Compliance of key herbicides with existing Forest Stewardship Council (FSC) standards, the key environmental certification body within New Zealand, is also reviewed.

Methods: Information obtained from a survey of six forest companies operating in New Zealand was used to identify major herbicides used by the New Zealand planted forest industry, estimate quantity of herbicides used on an annual basis and also determine changes in weed management practices motivated by certification.

Results: Glyphosate was the most widely used active ingredient in pre-plant weed control with terbuthylazine and hexazinone used most widely for post-plant weed control. Together these herbicides comprise 90% of the estimated 447 tonnes of active ingredient that is annually used. Average aerial application rates for these three active ingredients were estimated at 3.3 kg ha^{-1}, 7.0 kg ha^{-1} and 1.8 kg ha^{-1}, respectively.
Use of terbuthylazine and hexazinone is restricted on FSC-certified forests subject to derogation. Environmental certification has resulted in a shift from broadcast application of terbuthylazine and hexazinone to greater use of spot weed control in the first year after tree planting. Spot weed control can reduce the amount of active ingredient used by up to 89%. Non-chemical weed control is not widely used by the forest industry as it is not as cost-effective as current herbicide regimes.
A review of the literature indicated that, when used operationally and according to label registrations, these herbicides are unlikely to have any negative impacts on the planted forest environment. Although they have been detected in groundwater, under multiple land uses, concentrations were at levels below documented safe drinking standards. There are limited data for forest soil and no data on the effects of these herbicides on aquatic biota in New Zealand.

Conclusions: At present time there is insufficient information to support or refute the prohibition of terbuthylazine and hexazinone in New Zealand's planted forests. This has highlighted a need to conduct field studies to determine the fate and behaviour of terbuthylazine and hexazinone in planted forests in New Zealand.

Keywords: Environment; Herbicide; Hexazinone; New Zealand; Planted forest; Terbuthylazine; Weed control

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Background

Control of competing vegetation during establishment of forests planted for timber or fibre production is the single most important treatment affecting tree growth and survival, and therefore crop productivity (Wagner et al. 2006). In New Zealand, herbicides provide the most cost effective means of controlling competing vegetation in commercially planted forests and are currently used for both pre-plant and post-plant vegetation control (Rolando et al. 2011). Despite their importance for effective forest management, there is limited information on the types and amount of herbicide currently used in New Zealand planted forests. It is not known whether shifts in the amount and type of herbicide have occurred in response to pressure from certification bodies to reduce use of herbicides. This knowledge gap has highlighted a requirement to examine more closely the use of herbicides and their environmental fate within planted forests in New Zealand.

Globally, there is a trend to reduce herbicide use in forests (Thompson and Pitt 2003; Little et al. 2006; McCarthy et al. 2011). The pressure to shift away from herbicides is motivated by environmental policy operating at a national or regional level as well as voluntary subscription by forest growers to independent forest certification schemes, such as the Forest Stewardship Council (FSC) or the Programme for the Endorsement of Forest Certification (PEFC). Such certification schemes act to endorse sustainable forest management practices, often with a requirement to reduce and eventually eliminate herbicide use (Forest Stewardship Council 2007; Wilson 2012). This mandate has resulted in widespread use of glyphosate for forest weed control due to its low toxicity, residual action and cost. (Thompson and Pitt 2003; Willoughby et al. 2009). Environmental concerns around off-site migration and detrimental effects of herbicides on surface and groundwater quality are key drivers behind the increasing pressure to reduce herbicide use in planted forests. When addressing the potential environmental effects associated with herbicides, however, it is important that the context of their use is considered in association with the impacts from alternative management practices implemented to achieve the same goal. For example, used correctly, herbicides do not produce the adverse affects associated with severe fire and mechanical site preparation and can therefore act to minimise impacts on water quality, site productivity and forest sustainability (Neary and Michael 1996). According to Neary and Michael (1996) it could be argued that herbicide applications work to protect water quality and maintain site productivity by retaining nutrient-rich organic matter and soil-surface horizons on site.

Management of the competing vegetation in New Zealand's planted forests, predominantly comprised of *Pinus radiata* D. Don, is achieved primarily through the use of herbicides (Rolando et al. 2011). As over 60% of the planted forest land is certified by the FSC (New Zealand Forest Owners Association 2011/2012), there is a need for the forest industry to critically examine herbicide use and, where possible, consider a reduction in application thereof. Certification allows New Zealand forest companies access to value-added markets and also offers a means of attracting investment from the global financial sector. A 20% increase in the percentage of forest area certified over the past decade is a clear indication that certification is likely to remain a management preference. Moreover, the New Zealand forest industry is committed to the principles of sustainable forest management which is supported by the New Zealand Environmental Code of Practice for Plantation Forestry (New Zealand Forest Owners Association 2012) and the national initiative to develop the National Standard for Certification of Plantation Forest Management in New Zealand.

Using information obtained from a survey of forest vegetation management practices across forest companies in New Zealand, this paper summarises current herbicide use in New Zealand planted forests. Compliance of these herbicides with FSC principles and criteria is examined. The environmental fate of key herbicides identified in the survey is also reviewed to evaluate potential risks posed to the environment from their continued use for forest weed control.

Methods

Survey of herbicide use in New Zealand's planted forests

A survey of forest vegetation management practices across New Zealand forest management companies was used to identify the major herbicides in use by the forest industry, estimate the quantity of herbicides being applied to forest land on an annual basis and also determine changes in weed control regimes (chemicals and application method) motivated by certification with FSC over the past decade. Over the period January to March 2012, a sub-set of six companies operating in the New Zealand planted forest industry was surveyed to benchmark current pre- and post-plant vegetation control practices. The survey was emailed to forest managers of the major forest companies requesting details of their vegetation control operations (Table 1).

An estimate of the annual herbicide inputs for New Zealand plantation forests was made using two sources of information. Results from the survey were used to define typical use of herbicides. This information was combined with data from the New Zealand Forest Owners Association (http:www.nzfoa.org.nz; accessed February 2013) that quantified the restocked and newly planted area. For the estimation of annual herbicide use, it was assumed that: 1) average annual restocked and newly planted area is 50,000 ha (based on the average calculated for the period 2001 to 2009), 2) all newly planted and

Table 1 Summary of the information requested from regional staff of New Zealand forest companies surveyed on forest vegetation management operations

Topic	Information
General	Region of operation.
	Major weed species.
Pre-plant vegetation control	Details of chemicals, rates, frequency and method of application.
Post-plant vegetation control	Details of chemicals, rates, frequency and method of application.
Certification	Details of any changes in vegetation control motivated by certification.
	Details of any non-chemical methods employed in forest vegetation management operations.

restocked areas get an aerial pre-plant spray and first-year post-plant control (release), 3) first-year release operation is 40% aerial and 60% spot weed control, and 4) 50% of the restocked and newly planted area receives repeat aerial release between year 2 and year 4.

Results

Fifteen questionnaires were received from six forest companies representing approximately 41% of the New Zealand planted forest area. The regions covered by the responses broadly spanned the range of site types (as determined by mean annual air temperature and rainfall) on which plantation forests occur throughout New Zealand (Table 2).

Weed spectrum

Broom (*Cytisus scoparius* L.), gorse (*Ulex europeaus* L.), pine regeneration (*Pinus radiata*) and various species of grasses (Table 2) dominated the spectrum of key problematic weeds described by respondents. Responses described a greater diversity of weeds for the warm and wet central North Island and Northland regions than forest growing regions in the cooler South Island (Nelson, Marlborough, Canterbury, West Coast and Southland) or in drier North Island regions (Hawkes Bay and Gisborne).

Pre-plant control

All forest companies conducted pre-plant vegetation control, with the majority targeting this operation during late summer and autumn (between February and April). Pre-plant operations consisted of aerial applications of glyphosate (N-(phosphonomethyl) glycine) and metsulfuron methyl (methyl 2-(4-methoxy-6-methyl-1,3,5-triazin-2-ylcarbamoylsulfamoyl)benzoate), applied at average respective rates of 3.3 ± 0.68 kg ha^{-1} active ingredient (a.i.) and 0.12 ± 0.04 kg ha^{-1} a.i. in 150 ± 55 L water.

Certification has not affected the type and quantities of herbicide used, *per se*, in pre-plant vegetation control operations. However, an increasing awareness of the volumes of herbicide applied has resulted in some degree of change. This has included minimising the time between harvest and replant and adjusting herbicide rates to match the weed types present on the site. In some instances this may have resulted in increased herbicide use. For example rates of metsulfuron in the herbicide mixes were increased up to 0.18 kg ha^{-1} a.i. where a higher proportion of scrub and woody weeds were expected on the site.

Post-plant control

All forest managers carried out one post-plant vegetation control operation in the spring (September to December) following planting. Most, 11/15 (73%), conducted a second control operation one to four years after planting, with 8/15 (53%) of the responses indicating the operation was carried out only if necessary (to target the re-growth of broom or to reduce height of weeds when overtopping the trees). The method of application for the first post plant-control operation was either spot or aerial. The percentage split between application method ranged widely across companies and regions depending on weed load, soil type and terrain (Table 3). Terbuthylazine (N^2-tert-butyl-6-chloro-N^4-ethyl-1,3,5-triazine-2,4-diamine) and hexazinone

Table 2 Regions covered by the survey and the major weeds species identified (common name shown in brackets)

Region (Number of responses)	Major weeds
Northland (2)	*Ulex europaeus* (gorse), *Cortaderia selloana* (pampas), *Astelia trinervia* (kauri grass), *Solanum mauritianum* (woolly nighshade), *Gahnia* spp., *Senecio* spp. (fire weed), *Phytolacca octandra* (ink weed), *Hedychium gardneranium* (ginger)
Taupo/Bay of Plenty (Central North Island) (2)	*Buddleia davidii* (buddleia), *Cortaderia selloana* (pampas), *Ulex europaeus* (gorse) *Acacia* spp. (wattle), hardwoods (native), *Pinus radiata* (radiata pine) and eucalypt regeneration, various grass species, *Cytisus scoparius* (Scotch broom), *Rubus* spp. (blackberry)
Hawkes Bay/Gisborne (East Coast) (3)	*Ulex europaeus* (gorse), *Cytisus scoparius* (Scotch broom), various grass species, *P. radiata* (radiata pine) regeneration, native woody vegetation
Nelson and Marlborough (4)	Various grass species, *Ulex europaeus* (gorse) *Cytisus scoparius* (Scotch broom), *Pteridium esculentum* (bracken) and *Rubus* spp. (blackberry).
Canterbury (2)	*Ulex europaeus* (gorse), *Cytisus scoparius* (Scotch broom) and *P. radiata* (radiata pine) regeneration
West Coast South Island and Southland (2)	*Ulex europaeus* (gorse), *Cytisus scoparius* (Scotch broom), various grass species, native woody vegetation

Table 3 Summary of first-year vegetation control operations by each respondent for different regions showing: 1) the method of application (% of area managed with either aerial application or spot weed control), 2) the use rate per hectare of major active ingredients assuming broadcast (aerial) application to keep equivalence across regions and, 3) the diameter of the spot, where applicable

Region	Application method		Quantity of herbicide used		Spot diameter (m)[#]
	Aerial (% area)	Spot (% area)	terbuthylazine (kg ha^{-1})	hexazinone (kg ha^{-1})	
Northland	50	50	7.0	1.8	2.0
Bay of Plenty	0	100	7.2	1.8	1.8
Taupo	100	0	6.8	1.7	-
Gisborne	100	0	6.0	1.5	-
Hawkes Bay	50	50	7.0	1.8	1.4
Hawkes Bay	0	100	6.0	1.5	1.3
Nelson	40	60	6.0	1.5	1.5
Nelson	0	100	8.0	2.0	1.8
Nelson	0	100	9.2	2.3	2.0
Marlborough	20	80	8.0	2.0	2.0
Canterbury	0	100	6.0	1.5	2.0
Canterbury	94	6	7.0	1.8	-
Southland	70	30	8.0	2.0	1.4
Average	42	57	7.0	1.8	1.7

[#]The amount of active ingredients applied for an area where spot weed control is used would be reduced proportionately (see Table 4).
Note: two responses were excluded from the table as they were related to regions where terbuthylazine and hexazinone were not used exclusively.

(3-cyclohexyl-6-dimethylamino-1-methyl-1,3,5-triazine-2,4-(1*H*,3*H*)-dione) were the principal herbicides used for the first-year release operations (spot or aerial), and the only two actives cited for release operations in 13 out of the 15 questionnaires. The average application rate was 7 kg ha^{-1} active ingredient (a.i.) terbuthylazine and 1.8 kg ha^{-1} a.i. hexazinone, which approximately equates to an application of 17.5 L ha^{-1} of the most widely used products Agpro Valzine® 500 (Agpro NZ Ltd, Auckland) or Release KT™ (Orion Crop protection Limited, Auckland) (Table 3). One respondent indicated that, on sites with a predominance of grass weeds in Northland, haloxyfop-P-methyl (R-2-[4-[[3-chloro-5-(trifluoromethyl)-2-pyridinyloxy]phenoxy]-propionic acid), was used on sandy soils and hexazinone was used on clay soils during first-year release. Two respondents indicated use of clopyralid in combination with terbuthylazine during first-year release operations.

Four out of the fifteen responses (27%) indicated that certification has directly affected first-year release operations. This was described as either a shift towards use of spot weed control, a reduction in spot size or a change in the active ingredients used. Assuming a planting density of 833 stems ha^{-1} and an aerial application rate of 17.5 L ha^{-1} Valzine®, spot application reduces herbicide use by 74% and 89%, for spots with diameters of 2.0 m and 1.3 m respectively (Table 4). Besides using spot weed control to meet certification requirements, this method of application is also routinely used to manage competitive vegetation on steep slopes prone to erosion and sensitive areas close to neighbouring land use boundaries or wetlands. Spot weed control is used in sensitive areas as it removes the risk of herbicide drift, sometimes associated with aerial application. Spot weed control was also preferred where the level of competition was not expected to be severe.

Where a second weed control operation was carried out this was predominantly (60%) aerial application of the active ingredients clopyralid (3,6-dichloro-2-pyridine carboxlic acid), picloram (4-amino-3,5,6-trichloro-2-pyridinecarboxylic acid) and/or triclopyr (3,5,6-trichloro-2-pyridyloxyacetic acid) (applied as various formulated products) in 150 to 200 L ha^{-1} water. Application rates of these active ingredients in second year release operations were variations around 1.5 kg ha^{-1} a.i. clopyralid, 0.15 kg ha^{-1} a.i. triclopyr and 0.05 kg ha^{-1} a.i. picloram and were only applied when necessary (scrub weeds such as broom or gorse start to overtop the trees). A repeat application of terbuthylazine and hexazinone was used in one region only at rates shown in Table 3. In Northland where the difficult to kill sedges (*Gahnia* spp.) and grasses (such as *Cortaderia selloana*) occur hexazinone was also used in second release operations.

Table 4 The calculated quantity of the herbicide (Valzine®) and its active ingredients (terbuthylazine and hexazinone) applied for a range of spot diameters for an idealised stand established at a stand density of 833 stems ha^{-1} and treated at an equivalent standard broadcast application rate of 17.5 L ha^{-1} Valzine®

Spot diameter (m)	Valzine® applied in spot (L ha^{-1})	Terbuthylazine (kg ha^{-1})	Hexazinone (kg ha^{-1})	Percent of broadcast (%)[#]
1.30	1.93	0.77	0.19	11
1.50	2.52	1.03	0.26	15
1.80	3.71	1.48	0.37	21
2.00	4.58	1.83	0.46	26

[#]Also shown is the percentage of herbicide used in the spot relative to an application using broadcast methods.

Alternative weed methods

Three respondents indicated that alternative, non chemical, methods of weed control were either being investigated or used. The most common alternative used was oversowing with other species (such as grasses (*Holcus lanatus*) or legumes (*Lotus uliginosus*)) prior to planting. The purpose of such a treatment was to either suppress regrowth of scrub-weeds (when used in combination with spot weed control) or to reduce exposure on areas open to public view. However, the majority of responses indicated that alternative non-chemical methods of weed control were not being used as there was no benefit over existing weed control practices.

Amount of herbicide used in New Zealand planted forests

An estimated 7% of the total area planted to forestry (1.8 million ha) was treated annually with herbicide (125,000 ha) with a total annual input of herbicides estimated at around 447 x10^3 kg active ingredient (Table 5). This equates to a use rate of herbicides across the forest sector of 0.25 kg ha^{-1} year^{-1} with the predominant active ingredients being terbuthylazine (40%), glyphosate (39%) and hexazinone (10%) (Table 5). These figures are similar to those published by Manktelow et al. (2005) where forest herbicide use was estimated at around 0.23 kg ha^{-1} yr^{-1} a.i. (Table 6). Manktelow et al. (2005) also identified the same three active ingredients as the most commonly used.

Table 5 Estimate of the annual input of herbicides for New Zealand's planted forest area (1.8 million ha)

Active	Total annual input (kg)	Annual input (kg ha^{-1})
Glyphosate	175.0 x10^3	0.0972
Metsulfuron	5.8 x10^3	0.0032
Terbuthylazine	179.3 x10^3	0.0996
Hexazinone	44.8 x10^3	0.0249
Clopyralid	37.5 x10^3	0.0208
Triclopyr	3.8 x10^3	0.0021
Picloram	1.3 x10^3	0.0007
Total	447.4 x10^3	0.2485

Estimates of treated area assume 50,000 hectares is restocked annually (New Zealand FOA 2011/2012), and that 50% of these areas are retreated at age class 2, 3 or 4 using standard operational practice (1.5 kg ha^{-1} clopyralid, 0.15 kg ha^{-1} triclopyr and 0.05 kg ha^{-1} picloram). Estimates of herbicide use assume that first-year release is 40% aerial and 60% spot control.

Discussion

Herbicide use and compliance with FSC policy

The survey indicated that the major herbicides used by the forest industry were terbuthylazine, glyphosate, hexazinone, clopyralid, metsulfuron, triclopyr and picloram. These herbicides fall into four major classes: triazines, phosphonyls, sulfonylureas and pyridines – mostly herbicides with foliar post-emergent activity with the exception of picloram, hexazinone and terbuthylazine which have some residual activity. The forestry sector is a relatively low user of herbicides compared to other intensive primary industries in New Zealand. Annual herbicide use on a per hectare basis within forestry exceeds that of pastoral farming by 59% but constitutes only 11% and 2%, respectively, of usage within the arable and horticulture sectors (Table 6) (Manktelow et al. 2005).

Two of the three most widely used herbicides in New Zealand planted forests, terbuthylazine and hexazinone, are currently prohibited for use in forests certified by FSC (Forest Stewardship Council 2007). Together, these two herbicides provide excellent control of the major weeds of planted forests. A recent review of the indicators and thresholds for identifying highly hazardous pesticides for FSC, however, has indicated that terbuthylazine may be removed from the list of prohibited pesticides (Neumeister 2013). However, until a decision is made both terbuthylazine and hexazinone remain prohibited. A derogation is currently granted to permit forest owners temporary use of the prohibited chemicals subject to restricted use controls and research into alternative

Table 6 Use of pesticides by primary sectors in New Zealand (Mankeltow et al. 2005)

Sector	Total area (10^6 ha)	%Area[1]	Total kg (a.i. yr^{-1})	Mean pesticide loading (kg a.i. ha^{-1} yr^{-1})	Total use (%)
Pastoral farming	7.65	79.3	1,278 x10^3	0.17	35.90
Arable	0.14	1.5	344 x10^3	2.43	9.66
Forestry	1.74	18.0	463 x10^3	0.27	13.00
Horticulture	0.11	1.2	1,476 x10^3	13.19	41.44

[1]Area as a percentage of the total land area used by New Zealand's primary sectors.

chemical and non-chemical vegetation control. It is important that alternative, effective herbicides or non-chemical methods are identified since most weeds of planted forests in New Zealand are classified as highly invasive. In addition, regional legislation under the Resource Management Act (1991) requires that invasive weeds are either controlled or contained. Poor or no control of weeds on certified land could exacerbate the spread of invasive weeds, a major environmental and economic problem for New Zealand (Williams and Timmins 2002).

For inclusion on the FSC highly hazardous list, a chemical must be classified as persistent, toxic or biologically active, where derivatives remain and accumulate in the food chain beyond their intended use. Hexazinone, a triazinone, is a non-selective, post emergence contact herbicide and terbuthylazine, a triazine, is a broad spectrum pre- or post emergent herbicide absorbed mainly by plant roots (Tomlin 2006). The standard, relevant human and environmental toxicology data for terbuthylazine and hexazinone are shown in Table 7. According to the FSC Pesticide Policy, hexazinone has been banned for persistence, leaching potential and solubility and terbuthylazine was banned for its potential to bio-accumulate (Forest Stewardship Council 2007). The hazard to the forest environment when these herbicides are used for forest weed control, as identified by the FSC criteria, therefore needs to be critically examined. The key questions are: 1) when used for planted forest weed control what is the risk that terbuthylazine will leach into local water bodies and bioaccumulate to a level that is toxic? and 2) does hexazinone move out of the environment and accumulate in local streams to a level that is hazardous to aquatic life or drinking water quality?

The main processes by which herbicides can reach water bodies are preferential flow through the soil and from soil erosion (Neary et al. 1993; Holvoet et al. 2007). Additionally, spray drift can occur during aerial application that may result in the herbicide being carried out of the treated area to a nearby water body (Holvoet et al. 2007; Thistle et al. 2009). This last factor is largely controlled through the use of appropriate buffer zones to avoid direct application into streams and off-target vegetation (Ray et al. 1998; Richardson et al. 2004; Neary et al. 2009). The following discussion more closely examines the literature pertaining to the environmental fate of these two herbicides in forest environments and relates these findings to the forest industry in New Zealand.

Environmental fate of terbuthylazine and hexazinone in planted forests outside New Zealand

Because of its widespread global use, there is a substantial body of published literature, mostly from the USA and Canada, documenting the movement of hexazinone through forest watersheds and its impacts on terrestrial and aquatic flora and fauna (Mayack et al. 1982; Leitch and Flinn 1983; Neary 1983; Thompson et al. 1993; Bouchard et al. 1985; Lavy et al. 1989; Michael et al. 1999). Most of these studies indicate hexazinone to be of low toxicity to fish, frogs and invertebrates with no adverse effects recorded (Berrill et al. 1994; Mayack et al. 1982; Neary 1983; Thompson et al. 1993) (Table 7). At highest risk in the forest environment are freshwater algae as they possess the specific target sites for the active ingredient (Peterson et al. 1994). At a concentration of 2.9 mg L^{-1} (2.9 ppm), hexazinone was found to be highly toxic to 11 species of cyanobacteria, algae and duckweed (Peterson et al. 1994). Similarly, Thompson et al. (1993) showed that chronic exposure to hexazinone at concentrations of 1 mg L^{-1} (1 ppm) induced direct effects to freshwater phytoplankton with resulting impacts on zooplankton communities. Studies have shown that peak concentrations of hexazinone are typically highest following application and initial rainfall

Table 7 Human toxicology and environmental persistence data for hexazinone and terbuthylazine (Tomlin, 2006)

Herbicide	DT^a_{50} days	ADI[b] mg kg^{-1} bw	K^c_{ow} logP	K^d_{oc} mL g^{-1}	K^d_d mL g^{-1}	Solubility[e] mg L^{-1}	LD_{50} (rats)[f] mg kg^{-1}	LC_{50} (96 h) (trout)[g] mg L^{-1}	LC_{50} (48 h) (Daphnia)[g] mg L^{-1}	LC_{50} (14 day) (earthworms)[g] mg kg^{-1}	BCF[h] (potential)
terbuthylazine	30-60	0.004	3.2	162-278	2.2-2.5	8.5	1590	3.8-4.6	21-50.9	141.7	34 (low)
hexazinone	30-180	0.05	1.2	54	0.2	29800	860	>320	442	na	7 (low)

[a] The rate of degradation of pesticides in soils is often expressed as the half-life (DT_{50}), in years, months or days (Tomlin 2006).
[b] The Acceptable Daily Intake (ADI) value is the maximum quantity of chemical that humans can absorb in a day for their entire lifespan without showing any signs of illness (Tomlin 2006). bw = body weight.
[c] The octanol-water partition coefficient (K_{ow}) is the ratio of the concentration of a chemical in octanol and in water at equilibrium.
[d] The soil organic carbon (OC) affinity coefficient (K_{oc}) represents the soil distribution coefficient (K_d) normalised for soil organic carbon content.
[e] Solubility in water.
[f] The LD_{50} is the dose that kills half (50%) of the animals tested (LD = "lethal dose") (Tomlin, 2006).
[g] The Acute LC_{50} (hours) is the concentration in water that kills half (50%) of the animals tested (LC = "lethal concentration") (Tomlin 2006).
[h] BCF-bio-concentration factor; taken from the Pesticide Properties Database (PPDB), University of Herdfordshire. http://sitem.herts.ac.uk/aeru/footprint [accessed January 2013].
na: indicates data were not available.

events (Miller and Bace 1980; Leitch and Flinn 1983; Neary 1983; Bouchard et al. 1985). A number of trials have assessed the movement of hexazinone into stream water following operational application in forests (Miller and Bace 1980; Neary 1983; Bouchard et al. 1985). Levels of hexazinone in stream water ranged from below detectable limits to 2.4 mg L^{-1}. In all cases, however, levels of hexazinone declined rapidly to below detectable levels within six to seven months after application. The reported levels of hexazinone in streams did not support chronic exposure to levels of hexazinone greater than 1 mg L^{-1}, but rather fluxes of chemical at almost negligible levels over a period of months. Hexazinone is typically applied within New Zealand forest environments once every 30 years, frequently at levels below 0.5 kg ha^{-1} when spot control is used (Table 4). It therefore, seems unlikely an operational application of this herbicide would have any long-term negative environmental impact.

In contrast to hexazinone, there is relatively little information on the dissipation of and ecotoxicity of terbuthylazine when used in a forest environment and limited data on its potential to bioaccumulate, the reason it was prohibited. Ecotoxicology data on terbuthylazine indicate that it is considered moderately toxic to both cold and warm water fish, slightly toxic to aquatic invertebrates, and highly toxic to aquatic plants, algae, and estuarine and marine invertebrates (Table 7) (European Food Safety Authority 2011; Tomlin 2006). Bioaccumulation is defined as the process that causes increased chemical concentration in an aquatic organism compared to that in water and the bioaccumulation factor (BAF) is the ratio of the concentration of the chemical in the organism compared to that in water (Vallack et al. 1998; Mackay and Fraser 2000). From a scientific perspective there is no threshold defining problematic values of bioaccumulation. For rainbow trout exposed to terbuthylazine at 1% of the 50% lethal concentration (LC_{50}) value, Tarja et al. (2003) reported a BAF of between 6.2 and 8.1 for terbuthylazine at temperatures ranging between 4°C and 17°C, respectively. Beek et al. (1992) considered chemicals with a BCF of less than 30 to present no cause for concern. Mackay and Fraser (2000) suggest an octanol/water partition co-efficient (log PK_{ow}) of 5.0 or greater as a threshold for the onset of bioaccumulation and at 3.2 terbuthylazine sits well within this limit (Table 7). These studies question the rating assigned to terbuthylazine as likely to bioaccumulate and indicate an independent assessment is needed to determine whether or not the use of the chemical actually presents a threat to native New Zealand biota. Terbuthylazine is not considered a persistent chemical, DT_{50} in soil ranges between 30 days to 60 days (Table 7) and aqueous hydrolysis occurs over a similar period (Tomlin 2006). For a chemical that is only applied once or twice every 28 to 30 years, the potential to bioaccumulate will be limited as the chemical will not be in the environment long enough for this to occur.

Environmental fate of terbuthylazine and hexazinone in New Zealand planted forests

The fate and behaviour of pesticides including terbuthylazine and hexazinone, in New Zealand agro-ecosystems were reviewed about a decade ago (Sarmah et al. 2004). Terbuthylazine has been shown to be fairly immobile in the soil and to rapidly degrade and hexazinone shown to be very mobile in the soil and persistent (Close et al. 2005; Close et al. 2003; Close et al. 2006; James et al. 1998; Pang et al. 2005; Pang and Close 2001; Sarmah et al. 2005). For planted forests in New Zealand, there are two laboratory studies on herbicide soil adsorption (Watt et al. 2010; Rolando and Watt 2012). There are no larger scale catchment studies on herbicide impacts on terrestrial and aquatic flora and fauna for planted forests.

Data on the dissipation of both herbicides on a range of New Zealand soils is summarised in Table 8. Values shown for New Zealand soils exceed the ranges cited by Tomlin (2006) (Table 7 and Table 8) with implications for the behaviour of these herbicides, particularly terbuthylazine in New Zealand forest soils. Hexazinone was measured to be very mobile across most New Zealand soils, with a range in K_d values of between 1.4 mL g^{-1} and 2.8 mL g^{-1} reported for forest soils (Rolando and Watt 2012). Soil sorption (K_d) values for terbuthylazine in New Zealand forest soils were shown to range from 5.1 mL g^{-1} to 50.2 mL g^{-1}, depending on the percentage soil carbon, indicating that this herbicide is potentially only mobile in New Zealand forest soils having low organic carbon fractions (Table 7 and Table 8) (Watt et al. 2010). Soils that typically have low organic carbon, Recent and Raw soils, represent around 15% of the plantation forest estate (Watt et al. 2010) and are areas that could potentially be identified and labelled as high risk sites. If a risk based approach were used, application of terbuthylazine could be limited to sites with high organic carbon fractions where the potential for loss through leaching was low.

In New Zealand, the maximum acceptable value (MAV) for drinking water for hexazinone is 0.4 mg L^{-1} (0.4 ppm) and for terbuthylazine is 0.008 mg L^{-1} (0.008 ppm) (Ministry of Health 2008), values that are consistent with that used by WHO (World Health Organisation 2010). In a national survey of pesticides in New Zealand's groundwater in 2010, terbuthylazine was the most frequently detected pesticide, found in 10% of the wells sampled (Close and Skinner 2012). The highest level of terbuthylazine detected was 0.0058 mg L^{-1}

Table 8 The distribution coefficient, K_d, and soil organic carbon affinity coefficient, K_{OC}, for soil orders sampled in New Zealand for hexazinone and terbuthlyazine

Soil order	Soil organic carbon (%)	Hexazinone		Terbuthylazine		Land use	Reference
		K_d (mL g^{-1})	K_{OC} (mL g^{-1})	K_d (mL g^{-1})	K_{OC} (mL g^{-1})		
Allophanic	10.3	2.8	30	39.3	274	Planted forest	Rolando and Watt (2012)
Brown	5.2	1.9	37	16.9	322	Planted forest	Rolando and Watt (2012)
	6.8	1.0	40	3.0	42	Agriculture	Close et al. (2005)
	3.3	0.4	11	5.0	151	Agriculture	Close et al.(2005)
	3.9	1.8	45	6.9	177	Agriculture	Close et al.(2005)
Pallic	3.7	-	-	10.4	296	Planted forest	Rolando and Watt (2012)
Podzol	7.6	1.4	19	50.2	576	Planted forest	Rolando and Watt (2012)
Pumice	5.9	1.4	29	15.9	268	Planted forest	Rolando and Watt (2012)
Raw	1.0	-	-	5.1	499	Planted forest	Rolando and Watt (2012)
Recent	1.6	1.3	28	5.4	352	Planted forest	Rolando and Watt (2012)
	2.4	2.3	97	13.7	575	Agriculture	Close et al. (2006)
Ultic	3.8	2.8	30	14.6	406	Planted forest	Rolando and Watt (2012)

(0.0058 ppm) which is 73% of the MAV. In all other wells where it was detected, however, it was below 10% of the MAV (Close and Skinner 2012). Hexazinone was found in only 1.9% of the wells sampled, with the highest concentration detected of 0.0007 mg L^{-1} (0.0007 ppm) which is below 0.2% of the MAV. These values are below the LC_{50} values quoted for rainbow trout and *Daphnia* spp., both aquatic organisms used in standard ecotoxicity tests (Table 7). The wells included in the 2010 national survey of pesticides in groundwater represented a mix of land uses, mainly agriculture and horticulture, with no wells sampled with an associated forestry land use (Close and Skinner 2012). Terbuthylazine is used in both the agricultural and horticultural industries in New Zealand, as well as forestry (Manktelow et al. 2005). The wells sampled in the 2010 national survey of pesticides in groundwater represent deep groundwater and it is, therefore, not possible to draw conclusions regarding pesticide detection and associated land use. What these results do indicate is that levels of terbuthylazine and hexazinone in New Zealand groundwater do not exceed toxicity thresholds.

The results from the existing studies on fate and behaviour of terbuthylazine and hexazinone in New Zealand indicate that, under standard arable land use, neither of these chemicals persists in a manner that could be hazardous to soil or water quality. Considering that mean pesticide loading (kg a.i. ha^{-1} yr^{-1}) in forestry is approximately 10 and 50 fold less than that in the arable and horticultural sectors (Table 6), the risk to groundwater posed by herbicide use in the forestry sector (1–2 times every 30 years) can only be lower than that posed by agricultural and horticultural use (annual application). Data on the direct toxicity of these herbicides to a range of species assists in identifying the potential risks to the receiving environments in New Zealand. However, there are no data for either chemical on the risk posed to native soil and aquatic biota likely to be found in New Zealand planted forests, many of which are unique (Boothroyd 2009; Harding et al. 2004). The lack of information pertaining to the fate of these herbicides in New Zealand forest soils and waterways when used in routine forest weed-control operations means there is uncertainty around the risk they pose to the New Zealand planted forest environment.

Conclusions

Glyphosate, terbuthylazine and hexazinone were found to be the most widely used active ingredients in pre-plant (glyphosate) and post-plant (terbuthylazine and hexazinone) forest weed control operations. The prohibition of two active ingredients that constitute 50% of the total amount of herbicide used on planted forest land certified by the FSC would severely impact current forest weed control operations, unless viable, cost effective, alternative weed management options were found. The infrequent use of terbuthylazine and hexazinone within one rotation of approximately 30 years in New Zealand's planted forests considerably reduces the environmental risk of polluting ground and surface waters. In addition, wide use of spot weed control means the risk of off-site movement of these herbicides is reduced. Data from a recent national survey of pesticides in groundwater in New Zealand indicate levels of these pesticides are below that likely to be toxic to humans and the environment.

The data on which FSC based its decision to place hexazinone and terbuthylazine on its highly hazardous list were primarily data derived from laboratory studies or field trials conducted in environments that may be very different from those found in New Zealand planted forests. The paucity of data on the environmental impacts of these active ingredients in the New Zealand planted forest environment, however, means it is difficult to determine with a high degree of certainty whether or not the FSC classification is warranted when the herbicides in question are used in New Zealand planted forests. There is, therefore, a need to undertake empirical field studies to reduce this uncertainty and inform a risk assessment specific to New Zealand planted forests. Such an approach would ideally be undertaken over a long time period at the catchment scale.

If the indicators for identifying highly hazardous pesticides for FSC certified land and thresholds for concern are modified, and terbuthylazine is removed from the list of prohibited pesticides, the data presented and collated here support a low-risk profile of this herbicide in the context of current forestry practice. Assuming that the prohibition of terbuthylazine and/or hexazinone continues to be pursued, however, studies need to be conducted to determine if these herbicides can be gradually phased out and replaced with herbicides that meet certification requirements. Over the medium term, it may be sufficient to retain spot treatments of terbuthylazine and hexazinone as this markedly reduces use of these herbicides. As terbuthylazine and hexazinone are very effective herbicides that provide broad spectrum long-term weed control, with little phyto-toxicity to crop trees, their replacement is likely to have economic implications. Development of a national monitoring system for reporting of pesticide use in New Zealand planted forests may be one possible course of action that enables the forest industry to more clearly demonstrate its existing commitment to protecting the planted forest environment and to facilitate better documentation of annual herbicide inputs.

Competing interests
The authors declare that they have no competing interests.

Authors' contribution
Carol Rolando and Loretta Garrett developed the concept for this paper. Carol Rolando and Michael Watt conducted the industry survey and compiled the results section. Brenda Baillie and Loretta Garret conducted the literature review, global and local, on the impact of terbuthylazine and hexazinone on soil and water quality. Carol Rolando, with the support of all co-authors, brought the survey and literature review together to form the review presented in this paper. All authors read and approved the final manuscript.

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