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Review

The Risks Associated with Glyphosate-Based Herbicide Use in Planted Forests

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Abstract: Glyphosate-based herbicides are the dominant products used internationally for control of vegetation in planted forests. Few international, scientific syntheses on glyphosate, specific to its use in planted forests, are publically available. We provide an international overview of the current use of glyphosate-based herbicides in planted forests and the associated risks. Glyphosate is used infrequently in planted forests and at rates not exceeding 4 kg ha^{-1}. It is used within legal label recommendations and applied by trained applicators. While the highest risk of human exposure to glyphosate is during manual operational application, when applied according to label recommendations the risk of exposure to levels that exceed accepted toxicity standards is low. A review of the literature on the direct and indirect risks of operationally applied glyphosate-based herbicides indicated no significant adverse effects to terrestrial and aquatic fauna. While additional research in some areas is required, such as the use of glyphosate-based products in forests outside of North America, and the potential indirect effects of glyphosate stored in sediments, most of the priority questions have been addressed by scientific investigations. Based on the extensive available scientific evidence we conclude that glyphosate-based herbicides, as typically employed in planted forest management, do not pose a significant risk to humans and the terrestrial and aquatic environments.

Keywords: isopropylammonium; risk assessment; herbicides; glyphosate; forest vegetation management

1. Introduction

Glyphosate (CAS 1071-836) was commercially introduced by Monsanto in 1974 as a broad-spectrum post-emergence non-selective herbicide [1]. Since then, its use has expanded rapidly and it is currently the most widely used and successful herbicide worldwide [2,3]. Several factors contribute to the success and widespread use of this active ingredient, including: (i) ability to translocate throughout treated plants and control re-sprouting in perennial weeds; (ii) generally favourable environmental profile including strong binding and immobility in soils and rapid biodegradation in most soils, water and sediments; (iii) plant-specific mechanism of action (5-enolpyruvyl-shikimate-3-phosphate synthetase or EPSPS enzyme of the shikimic acid pathway of plants) and (iv) innately low toxicity to animals [3,4] and minimal ecological impact in forest ecosystems [5–8]. Data generated by more than four decades of laboratory and field studies relating to multi-sectoral uses of glyphosate-based herbicides, would suggest that this is perhaps the most intensively studied herbicide of all time.

Until recently, the development of glyphosate resistant weeds associated with intensive use in genetically modified agricultural cropping scenarios was commonly considered the greatest risk to continued widespread use of glyphosate. This problem highlighted the need for greater innovation and diversity in weed management practices, particularly in the agricultural sector where the majority of use occurs [9,10]. However, the recent classification of glyphosate as a probable human carcinogen [11] has heightened and refocused public concerns on issues relating glyphosate use and human health. The public attention on glyphosate has also highlighted the broader social issues relating to glyphosate use such as increasing reliance on genetically modified crops [12], corporate control over food and fibre production (e.g., [13]), pesticide use in general terms or general concerns regarding over-exploitation of natural resources (e.g., [14]).

A fundamental precept of chemical toxicology and associated estimations of risk to either human or environmental health is the requirement to consider exposure [15,16]. Given imperfect knowledge and uncertainties, which are associated with any assessment of risk [15], conclusions drawn from risk assessments are typically framed in probabilistic rather than absolute terms. That is, risk estimates are generally expressed based on probability of occurrence either quantitatively or categorically as low, moderate or high. What constitutes a low or acceptable risk probability is a matter of judgement and requires consideration not only of risk, but also of benefit [17] and is to some degree at least inherently subjective. In the case of glyphosate, a multitude of independent scientific reviews and regulatory risk assessments exist and commonly conclude that glyphosate-based herbicides, when applied in accordance with the product label and applicable best management practices, do not pose a significant risk to human or environmental health [1,4–8,18–25]. Since its public release, the International Agency for Research on Cancer (IARC) [11] declaration on glyphosate indicating a potential risk to humans has been challenged by numerous scientists and regulatory risk assessment agencies worldwide [23,24], as well as by a special joint working group of the Food and Agriculture Organisation of the United Nations and the World Health Organisation [26], all of which concluded that glyphosate uses are unlikely to pose an actual risk of carcinogenicity or any other toxic effect to humans.

Relatively few scientific syntheses or risk assessments on glyphosate specific to its use for the management of vegetation in planted forests are available. Moreover, those that have been conducted tend to be regionally specific or not readily available in the public domain [5–8,27]. Fundamental to toxicological and ecotoxicological evaluations is a quantitative understanding of the probability, duration, magnitude and potential routes of exposure that are largely controlled by sector-specific use patterns, such as for those practiced in planted forests. In this paper, an international overview of the current use of glyphosate-based herbicides in planted forests is provided together with any associated specific risks and benefits. The intention is to evaluate the importance of this herbicide to the planted forest industry as well as the evidence for associated exposure and risk to humans, and terrestrial and aquatic biota. Reliance has been made on a significant range of prior risk assessments and independent expert reviews to summarize much of the fundamental toxicology and ecotoxicological data available on glyphosate-based herbicides. In augmenting this information, we have integrated our own forest sector specific knowledge relating to use patterns, characteristics of the receiving environments and the fate of the herbicide therein, as these are primary determinants of potential exposure and risk to humans, terrestrial wildlife and aquatic biota (Figure 1).

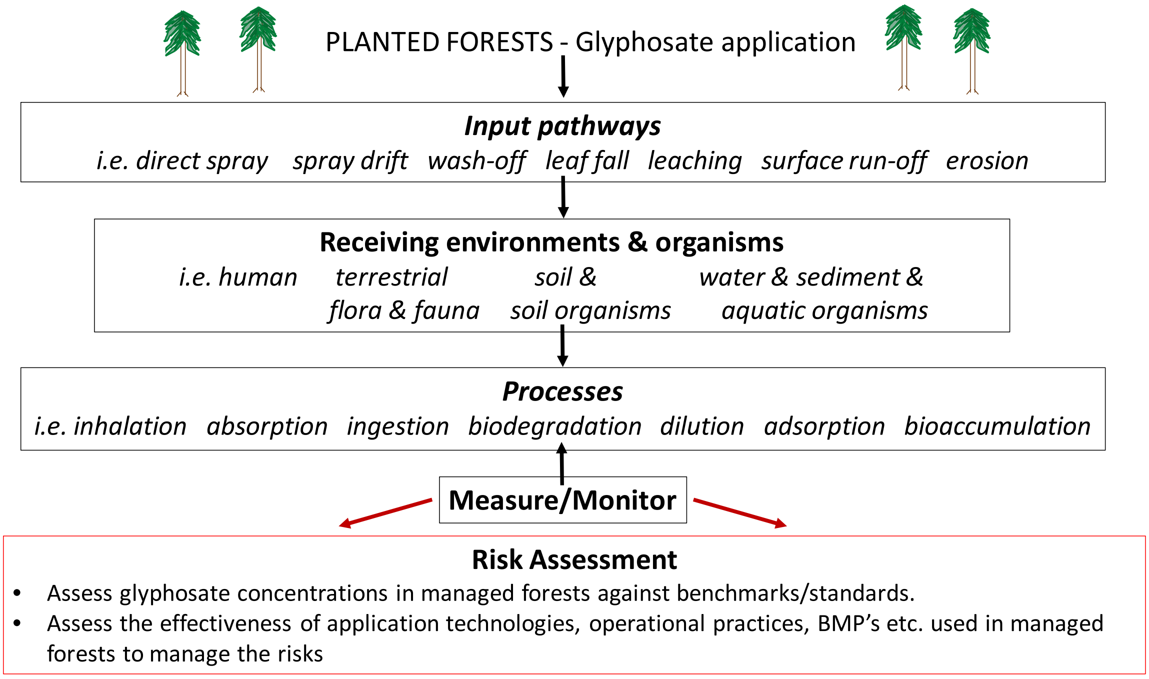

Figure 1. Framework used to undertake the risk assessment of glyphosate use in planted forests.

2. Glyphosate-Based Herbicide Use in Planted Forest Management Internationally

Worldwide, the influence of competing vegetation has been shown to have both short- and long-term negative impacts on timber production [28]. As such, vegetation management is considered a critical silvicultural practice, with the development of integrated competition control strategies. In forest vegetation management programs internationally herbicides represent one of several different options that may be used by foresters to enhance regeneration and planting success and thus sustainable use of the renewable resource from which a wide variety of different wood products are derived. As humans around the world utilize forest resources and derivative products extensively to meet basic needs such as for fuel, home construction and writing materials, as well as for a multitude of other needs, forest owners are responsible for assuring environmentally responsible and sustainable management of this resource [29].

Applied either on its own, or in conjunction with other herbicides or treatment options (i.e., mechanical site preparation, fire), glyphosate has been used for many years to prepare sites for planting of young trees (pre-plant application), or for the complete, or selective control, of competing vegetation after the tree crop has been planted (post-plant application) [27,30–35]. Such uses are directed at assuring efficient and cost-effective regeneration of the forest subsequent to harvest. The low-cost, broad spectrum and relatively low human and environmental toxicity of glyphosate have resulted in it becoming the active ingredient of choice for weed control in planted forests in many regions worldwide (Table 1).

In forest vegetation management programs, herbicide applications are typically made during the establishment phase, considered as the first two to three years of a rotation or until canopy closure occurs [28]. In assessing the risks associated with herbicide use in planted forest management the unique characteristics of the context of use in terms of temporal and spatial scale, receiving environment, degree of regulation and overall management, must be considered. For example, much unlike repetitive applications to the same area year over year in many agricultural cropping scenarios, glyphosate-based herbicides are typically applied only once or twice to the same area of planted forest through a rotation period that may range from ~8 years (e.g., *Eucalyptus* plantations in South Africa) to more than 50 years (e.g., *Picea* plantations in Canada). In some countries, only a small portion of the overall forested land base is actually harvested, planted and treated in any given year. For example, in Canada for the 2015 reporting year, national use statistics demonstrate that approximately 765,269 ha (~0.2% of the productive forest land base) was harvested to derive economic benefits. More than half of this harvested area (436,715 ha) was replanted, with the remainder being allowed to regenerate naturally. In this same year, only 105,811 ha were treated with a chemical herbicide, 94% of which was treatment with the herbicide glyphosate and almost entirely on the planted forest area [36]. During 2011, respondents to a survey about herbicide use on industrial forest land reported application of herbicides to 4.4% of the total area under management in the USA. By USA region, respondents applied herbicides to 0.26%, 2.6%, and 5.6% of the total area under management in the North, Pacific Northwest, and South, respectively [35].

Actual rates of glyphosate use in planted forest management internationally (mainly as formulated products containing the isopropylamine salt) range from 0.3 to 3.5 kg active ingredient (a.i.) per ha (Table 1 and Table A1). Higher rates are typically applied only on particularly difficult to control competitor species or on particularly productive sites where competitive advantage goes to pioneer plant species that establish quickly following opening of the canopy and/or site disturbance. Glyphosate-based herbicide use in planted forest management varies with region or country internationally. An overview of some typical application profiles is discussed.

Table 1. Estimated use of glyphosate and method of application for planted forest management in New Zealand, Canada, Australia, Chile, USA and South Africa.

Country	Amount (Tonnes Annum^{-1})	Application Rate (kg a.i. ha^{-1})	Timing of Application	Method of Application (Manual/Aerial)	Reference
New Zealand	175***	3.0–3.5	Pre-plant only	Aerial only	[37]
Canada	275 *	1.9–2.7	Typically post plant	Aerial	[7]
Australia	200–250 ***	0.3–3.2	Mainly pre-plant	Ground based mechanical and aerial	[31,38,39]
Chile	200–295 ***	2.0–2.5 **	Pre-and post-plant	Manual only	[40]
USA	185 ***	1.0–3.0	Mainly pre-plant	Aerial only	[35,41]
South Africa	146–193 ***	0.7–1.0	Pre-plant and post-plant	Aerial (pre-plant application) and manual (post-plant)	[33]

* Decadal average (2005–2015) as calculated from National Forest Database Program data for glyphosate use in kilograms per annum 275,232 kg year^{-1} converted to tonnes per annum. Source data: [42]. ** Made in 2–3 manual applications of 1.5 kg a.i. ha^{-1} year^{-1}, where a.i. refers to glyphosate as the active ingredient, Perscomm: Zapata, A. Subgerencia Planificación Silvícola, Gerencia de Silvicultura, Forestal Mininco S. A. and Damian Almendras, Aruaco, Chile. *** derived glyphosate use for silvicultural regimes using species, end-product and rotation length data.

2.1. Australasia

In New Zealand, glyphosate is one of the most important herbicides used for the management of competing vegetation in forests prior to commercial tree planting, with very limited use post-planting i.e., it is typically applied once in a rotation of 25 to 30 years [43] (Table 1). Glyphosate is applied, almost exclusively, aerially in late summer and early autumn, in combination with metsulfuron methyl, at respectively ~3.5 kg a.i. ha^{-1} and ~0.12 kg a.i .ha^{-1} in 150 L water. The application is made after harvesting shortly before the site is replanted when a high degree of organic debris, or logging slash, is present [44]. A review by Rolando et al. [43] indicated that commercial forests in New Zealand use an estimated 175 tonnes of glyphosate per annum for management of competitive vegetation during site preparation (Table 1). Based on these data, glyphosate ranks as the third highest used herbicide across the planted forest industry in New Zealand. A survey in 2002/2003 indicated that 42% of total glyphosate use in New Zealand is associated with management of vegetation in planted *Pinus radiata* forests with the remainder used in the horticultural and pastoral farming systems [37].

In Australia, glyphosate is principally used in pre-plant vegetation control operations in both softwood and hardwood planted forests, with limited use post-planting (Table 1). The herbicide is mainly broadcast via ground based machine or by helicopter, with use of hand-spraying limited to buffers, right-of-ways and sensitive boundaries [31]. The maximum label rate is 3.36 kg a.i. ha^{-1}, with use rates generally not exceeding 2.88 kg a.i. ha^{-1} (Gillie personal communication [40]). While no published data on the total amount of glyphosate used in planted forests in Australia was available it was estimated that use of glyphosate in Australian planted forests was in the range of ~200 to 250 tonnes annum^{-1} (Table 1).

2.2. South Africa

A variety of hardwoods and softwoods are grown in South Africa for production of a range of end-products (saw-timber, pulpwood, poles and mining timber). Establishment, or regeneration, of planted forests may be through re-planting (all genera), or coppicing (eucalypts). The variation in site productivity, regeneration and management regimes means a diversity of vegetation management practices are used [45]. Competing vegetation is controlled through a combination of physical control (manual hoeing or slashing) and application of herbicides. The predominant herbicide used is glyphosate (Table 1), where in South Africa, forestry accounts for 4% of the total glyphosate used [46].

Glyphosate applied as a pre-plant spray may be sprayed aerially (seldom), or manually using knapsack sprayers (more common) at 1.76 to 2.32 kg a.i. ha^{-1} [33]. All post-planting applications of glyphosate are via knapsack sprayers, either as a broadcast or directed/spot application depending on the size of the trees [47,48]. Between planting and canopy closure (<2 years), a eucalypt pulpwood stand will typically receive one broadcast application of glyphosate (with cones for tree protection), followed by two to three directed applications [47]. The duration of vegetation control in pine compartments is typically longer due to slower initial tree growth, requiring an additional two directed spot sprays in years three to five [48]. In South Africa, glyphosate is also used to manage secondary coppice regrowth in coppiced eucalypt stands where it is applied as a directed foliar spray at 1.2% (441 g a.i. L^{-1}) onto the foliage of secondary coppice regrowth until canopy closure [49]. Typically, this may involve in total two to four applications over two years equating to 1.94 to 3.88 kg a.i. ha^{-1} annum^{-1} for each of the two years.

Targeted noxious weed control is carried out periodically in all planted forests, mainly with the use of glyphosate applied at higher rates (2.20 to 3.48 kg a.i. ha^{-1}). The control of noxious weeds is not limited to planted areas which only make up ~70% of the area owned by forest companies in South Africa, but also includes non-afforested and conservation areas.

2.3. The United States of America

An estimate of total annual use of glyphosate in planted forests in the USA could not be obtained; however, approximately 1% to 2% of total glyphosate use in the USA is for forest management with the majority associated with use in the agricultural and horticultural sectors [50]. A recent herbicide use survey of industrial forest land (excluding non-industrial privately owned forest land) in the USA provided some information as to the use and application of glyphosate in planted forests [35]. The survey indicated that glyphosate (alone or as a mix) was applied over ~72,000 ha in 2011 and ranked as the fourth most widely used herbicide on industrial forest land [35]. Glyphosate was applied mainly for site-preparation (pre-plant) and mainly broadcast via helicopter, at average use rates of between 1.0 to 3.0 kg a.i. ha^{-1}, although higher use rates were recorded for some sites (up to 7.85 kg ha^{-1}). This use rate equates to an estimated national average for industrial forest land of ~188 tonnes for 2011, noting that inclusion of non-industrial privately owned forest land would increase this estimate (Table 1).

2.4. Canada

Canada's vast forested land base (347 million ha) is owned almost entirely by the public, and managed on their behalf by various provincial and territorial governments. At the national level, approximately 66% of the forest land area harvested in any given year is regenerated without herbicide intervention. The remaining 34%, (typically the most productive sites with greatest vegetative competition levels) is replanted to replace harvested conifers, and herbicides are used to ensure effective re-establishment of newly planted seedlings. Detailed records of herbicide use as well as other silvicultural statistics at both the provincial and national level are maintained and publicly accessible through the National Forest Database Program website (http://nfdp.ccfm.org/). Long-term trends continue to show that glyphosate-based herbicides dominate forest sector use patterns, continuously representing more than 95% of the total area treated in each year since 1990. In Canada, aerial applications using either rotary wing or fixed wing aircraft predominate, with ground applications on average since 1992, comprising only about 18% of the total area treated annually, largely for treatments near sensitive areas. Typically, applications are made within 1 to 3 years post-planting and involve rates that vary depending upon province and year, but with long term averages ranging from 1.9 to 3.4 kg a.i. ha^{-1}. In terms of total product applied in the Canadian forest sector, the long term annual average (1992 to 2014) was 290,990 kg with data showing a rather marked trend of decline over the past decade. In Canada, owing to the relative tolerance of spruce and other conifers later in the summer season, glyphosate-based herbicides are applied directly over top of planted seedlings to control diverse mixtures of competing vegetation including both woody and herbaceous competitors, and particularly on rich sites with the greatest competition levels.

2.5. Other Regions

Glyphosate is widely used for vegetation control in the management of planted hardwood and softwood forests in Chile applied either alone or in combination with other active ingredients [27]. For pre-plant vegetation control, or site preparation, rates of application vary according to the type of vegetation on site. For post-planting control of competitive vegetation glyphosate is applied manually as a directed spray to the inter-row, or with a shielded boom sprayer if terrain allows, generally at rates of around 2 to 2.5 kg ha^{-1}. As in South Africa, glyphosate is also used in the management of coppice [27] and total use has been estimated to be greater than 200 tonnes per annum.

Herbicide use patterns in forest management in the European Union are generally substantially lower than that for the intensively managed commercial plantations of the southern USA, Australia, South Africa, Chile and New Zealand [32]. However, in a survey of forest vegetation management practices across Europe conducted in 2009, Willoughby et al. [32] reported that glyphosate was the most used forest herbicide in 12 of 18 surveyed European nations. Most application was ground based via knapsack or machine spraying.

3. Environmental Fate of Glyphosate-Based Herbicides in Forests

3.1. Initial Deposition and Fate in Terrestrial Vegetation

The majority of glyphosate-based herbicides, applied either aerially or manually in managed forests, are intercepted by the competing vegetation canopy [51–54]. Once on the foliage, glyphosate is rapidly absorbed and translocated within the plant [53,55]. The time for glyphosate rain fastness (where the glyphosate has either dried or been sufficiently absorbed to maintain its effectiveness) varies from several hours to several days depending on the characteristics of the targeted weed species and the specific formulation applied [27,53]. Until rainfastness has been achieved, glyphosate is vulnerable to wash-off from heavy dew and rainfall events.

North American studies, across a wide range of environmental gradients, have shown that the majority of glyphosate foliar residues dissipate within a month of application under operational conditions in managed forests. Vegetation characteristics, temperature, humidity and timing of rainfall events (particularly within 24 h of application) were key factors influencing degradation rates [27,51–54]. The half-life of glyphosate (DT_{50}) is commonly used as a measure of degradation processes and persistence in the environment. The foliar DT_{50} for glyphosate ranged from less than one day to 14 days where application rates ranged from 1.98 to 3.3 kg a.i. ha^{-1} [51,53,56]. In a study conducted by Thompson et al. [53], the time for 90% of the foliar glyphosate to dissipate was less than 16 days. Where glyphosate was aerially applied in forests at a higher rate of 4.12 kg a.i. ha^{-1} (the maximum registered rate and about 3× the normal rate), across a range of climatic zones in the USA, 96% of the glyphosate in the overstorey vegetation dissipated within 30 days [51].

3.2. Fate in Litter and Soils

Most studies show that at the time of application the density of vegetation cover is a key factor influencing the amount of glyphosate reaching the forest floor, either from direct spray or spray drift [51,52,54,57]. In the post-application period an initial decline in glyphosate in the upper levels of forest soils was often followed by an increase in concentrations in the following few days or weeks. Sources of residues included dew fall, wash-off from rainfall events, (particularly within 24 h of application), or leaf drop from overhead vegetation (Figure 1), often contributing to large increases in forest floor glyphosate residues [51,52,54,57]. For example, in the Newton et al. [52] study in Oregon Coast Range, mean residue concentrations of glyphosate in forest litter, following aerial application of glyphosate (3.3 kg ha^{-1}) were 5.0 mg kg^{-1} on the day of application, doubled during a rainfall event the following day, then declining rapidly to 0.2 mg kg^{-1} by day 55.

Most forest soils are characterised by the presence of litter layers with high organic carbon content and as a result provide an effective sink for glyphosate residues. Glyphosate acid itself is zwitterionic, carrying both a positive and negative charge under typical environmental pH conditions but in different proportions depending upon the exact pH [27,58,59]. It is the zwitterionic character of the glyphosate molecule which is responsible for its tendency to sorb strongly to organic matrices or clay minerals. On reaching the soil environment, either directly or indirectly, the breakdown of glyphosate in forest floor litter and soils is generally rapid (litter: DT_{50} 8 to 19 days; soil: DT_{50} 5 to 40 days) [52,54,57], with microbial degradation considered the primary degradation pathway [52,60,61], although there may be some limitations on the ability of microorganisms to completely mineralise glyphosate and its primary metabolite, AMPA [62].

Even when glyphosate remains in forest soils, leaching into aquatic environments is not considered to be a significant transfer pathway [51,52]. This is because for most soils within the typical pH range (4 to 8 pH), glyphosate is present in the form of an anion and bonds tightly to both the organic matter and mineral component of soils, as is indicated in its high sorption constants (Table 2) [22,51,52,58,63]. This is supported by studies on the environmental fate of glyphosate in forest soils, showing glyphosate retention mainly within the top 15 cm of soil depth, with comparatively lower concentrations occurring in the mineral soil layer [52,60,61]. All studies conducted within forest catchments have reported minimal or no evidence of leaching via movement down the soil profile, slope runoff or subsurface flow, irrespective of the soil type, climatic conditions, application rate and the glyphosate product used [51,54,57,61]. For example, even in sandy boreal forest soils in Ontario, Canada, most of the glyphosate (95% at any given time) was retained within the organic layer [61]. Vertical mobility was not observed in forest sites across several regions in the USA [51,54,61].

Table 2. Generic human toxicology and environmental persistence data for glyphosate and isopropylammonium salt [5,23,38,41,64,65].

Parameter	Unit	Glyphosate Isopropylammonium	EFSA 2015 Recommendations
Kow (log P)		<−5.4 (20 °C)	
Solubility in water	g/L	1050 (25 °C, pH 4.3)	
Koc		1424	
pKa		5.77	
ARfD	mg/kg bw		0.5
NOAEL (2 years) rats	mg/kg bw	31	
AOEL	mg/kg bw		0.1
Drinking water standard #	μg L^{-1}	Australia, 1000; USA, 700	
Acute Oral LD_{50} (rats)	mg/kg bw	>5000	
Inhalation LC_{50} (4 h) (rats)	mg/L air	1.3	
Acceptable daily intake (ADI)	mg/kg bw per day	1 (2004)	0.5
WHO Toxicity class		2B	
WHO Hazard class		III (slightly hazardous)	
LC_{50} Trout (96 h)	mg/L	>1000	
LC_{50} *Daphnia* (48 h)	mg/L	930	
EC_{50} Algae (72 h)	mg/L	72.9	
LC_{50} Earthworm (14 day)	mg/kg soil	>5000	
LD_{50} Bee	μg/bee	>100	

DT_{50} soil	Days	1–130
DT_{50} water	Days	<190
Major metabolite in soil and water		metabolised to aminomethylphosphonic acid (AMPA)

EFSA—European Food Safety Authority; ARfD—Acute reference dose; NOAEL—No observed adverse effect level; AOEL—Acceptable operator exposure level; ADI—The acceptable daily intake value is the maximum quantity of chemical that humans can absorb in a day for their entire lifespan without showing any signs of illness, bw = body weight; DT_{50}—The rate of degradation of pesticides in soils is often expressed as the time to 50% dissipation (DT_{50}) in years, months or days; K_{ow}—The octanol-water partition coefficient is the ratio of the concentration of a chemical in octanol and in water at equilibrium; pKa—acid dissociation constant; K_{oc}—The soil organic carbon (OC) affinity coefficient represents the soil distribution coefficient (K_d) normalised for soil organic carbon content; LD_{50}—is the dose that kills half (50%) of the animals tested (LD = "lethal dose"); LC_{50}—is the concentration in water that kills half (50%) of the animals tested (LC = "lethal concentration") and EC_{50} is the "Effective Concentration", that is the concentration which has some deleterious effect, other than lethality, on 50% of the animals tested. [#] Neither the World Health Organisation, nor South Africa and New Zealand have established a drinking water standard for glyphosate and AMPA because of its occurrence in drinking-water at concentrations well below those of health concern [66–68].

3.3. Fate in the Aquatic Environment

On the day of herbicide application, glyphosate can potentially enter freshwater environments within forests either from direct spray or spray-drift [69] or possibly accidental spillage [63]. Some of the highest concentrations of glyphosate in water bodies are therefore detected on the day of herbicide application, although these are typically below thresholds of significant biological impacts in terms of both exposure magnitude and duration. The highest concentrations detected have been in association with either operational [52] or experimental over-spraying of waterbodies [56,70] (Table 3). During the immediate post-application period, mobilisation of glyphosate residues from foliage, litter or soil via wash-off from heavy dew, rainfall events, and mobilisation of in-channel or riparian herbicide residues during high flow events, can provide additional sources of glyphosate to aquatic environments [51,56,71]. As discussed, transfer of terrestrial sources of glyphosate to aquatic environments via leaching, run-off or surface erosion, are unlikely to be major input pathways in forested environments and these processes are considered low risk.

Table 3. Planted forest field studies on the aquatic fate of glyphosate. References shown in square brackets.

					Water			Sediment	
Location	**Waterbody**	**Application Method**	**SMZ Width (m)**	**Glyphosate kg a.i. ha^{-1}**	**Max. Conc. ($\mu g\ L^{-1}$)**	**DL ($\mu g\ L^{-1}$)**	**DT_{50}**	**Max. Conc. ($\mu g\ L^{-1}$)**	**DL ($\mu g\ L^{-1}$)**
Oregon, USA [52]	stream	aerial	0	3.3	270 [b,#]		~≤1 day	~550	
British Columbia, Canada [72]	stream	aerial	0	3	23 [b]/100 [c]	5		400	40–100
British Columbia, Canada [72]	stream	aerial	60–100	3	<DL [b]/25 [c]	5		200	40–100
British Columbia, Canada [72]	stream	ground	10	0.5–1.5	<DL [b]/<DL [c]	5		50	40–100
British Columbia, Canada [72]	stream	aerial *	50–100	1.54	<DL [b]/<DL [c]	5		<DL	40–100
Manitoba, Canada [73]	ponds (*n* = 4)	aerial	0	0.89	16–141 [b]	0.25–0.50	1.5–3.5 days		
British Columbia, Canada [74]	stream	aerial	100	1.78	<DL	5			
British Columbia, Canada [74]	stream	ground	10	1.4	<DL	5			
British Columbia, Canada [60]	ephemeral stream (750)	aerial	0	2	<1.5 [b]; ~143 [c]	0.1		580	30
British Columbia, Canada [60]	stream (1600)	aerial	0	2	162 [b,#]; ~130 [c]	0.1		6800	30
British Columbia, Canada [60]	ephemeral stream	aerial	10	2	<DL	0.1			30
British Columbia, Canada [60]	ephemeral stream (1450)	aerial	10	2	2.47 [b]	0.1		<DL	30
Oregon, USA [51]	stream/pond	aerial	0	4.12 [a]	0.03/0.9 [b]	0.001	≤10 h	110/2360	50
Michigan, USA [51]	stream/pond	aerial	0	4.12 [a]	1.24/1.7 [b]	0.001	≤10 h	690/1920	50
Georgia, USA [51]	stream/pond	aerial	0	4.12 [a]	0.04/1.0 [b]	0.001	≤10 h	180/260	50
New Brunswick, USA [75]	stream	ground-based	65	1.67	<DL	25			
Ontario, Canada [70]	wetlands (*n* = 24)	aerial—over wetland	0	1.07–2.14	1950 [#] (mean 330) [b]	0.02			
Ontario, Canada [70]	wetlands (*n* = 11)	aerial—alongside wetland	0	1.07–2.14	(mean 180) [b]	0.02			
Ontario, Canada [70]	wetlands (*n* = 16)	aerial—buffered wetland	30–60	1.07–2.14	310 (mean 30) [b]	0.02			

SMZ—Stream Management Zone, an area along both sides of flowing body of water where extra precautions are taken during forest management operations, including those involving herbicide applications, to protect water quality; DL—maximum analytical detection limit; Max. Conc.—maximum concentration; DT_{50}—The rate of degradation of pesticides in water is often expressed as the time to 50% dissipation in years, months or days; [a] maximum registered rate, approx. 3× normal rate; [b] maximum concentration on the day of herbicide application; [c] maximum concentration during, or following, a rainfall event post-herbicide application; ~ approximate value estimated from graphs; * 2% of a 14,000 ha catchment; [#] experimental over-spraying of the waterbody.

Regardless of input pathways, once in the aquatic environment, most forest studies recorded a rapid decline in glyphosate concentrations in waterbodies following herbicide application or rainfall events. Field studies show DT_{50} for glyphosate of <5 days (Table 3). Glyphosate residues in streams and lentic bodies such as ponds and wetlands typically dissipated to below detection limits within 15 days of application [51,52,56,70,76]. These short time frames indicate a rapid breakdown or reduction of glyphosate in the water column, either by adsorption into benthic and suspended sediments, through microbial breakdown within the freshwater ecosystem (as evidenced by the low and transitory presence of AMPA) or downstream dilution, particularly in lotic water systems [51,52,56,73,76].

The highest potential for glyphosate persistence in aquatic environments is in systems which are deep, cold and relatively biologically inactive or oligotrophic systems. In such systems, glyphosate may be more persistent in both the water column and in bottom sediments. Some studies have documented residues in benthic sediments as being detectable for up to 18 months post-application in forested streams [51,52,56,76]. The high adsorption capacity of sediment for glyphosate has frequently resulted in higher peak concentrations in sediments compared with water (Table 3), that persisted for longer periods of time, even when the active ingredient was present in only small quantities in the water column (Table 3). It is likely that this process is a primary pathway for removal of glyphosate from the water column in forested freshwater environments [52,56,73,77,78].

4. Risk of Glyphosate-Based Herbicides to the Forest Environment

4.1. Direct Effects

The World Health Organisation has classified glyphosate as slightly hazardous (Class III) [64]. The toxicology data in Table 2 provides a benchmark, against which to assess the probable risk of glyphosate to planted forest terrestrial and freshwater environments when applied under operational conditions. Although isopropylamine is the main glyphosate salt applied in managed forests (Table A1) for the purposes of the risk assessment, the range of glyphosate salts used by this sector were assumed to have similar toxicological and ecotoxicological profiles [65,79]. This is intuitively reasonable since upon release into most natural environments all glyphosates salts readily dissociate to yield the glyphosate free acid molecule.

Given that glyphosate is an herbicide, non-target vegetation is particularly at risk, primarily from spray drift or accidental over-spraying. North American studies across a wide range of environmental gradients have shown that the majority of glyphosate foliar residues dissipate within a month of application under operational conditions in managed forests, indicating that the period of greatest risk for off-site transfer, is the immediate post-application period. The rapid uptake in plants and strong sorption to soils, clay minerals or other organic materials essentially immobilize glyphosate and minimise off-site movement unless there are major storm events within a few hours of treatment or where surface water flows are so great they are actually mobilizing soil particles with adsorbed glyphosate.

Terrestrial fauna residing in forested areas treated with glyphosate are potentially at risk of exposure to glyphosate via direct spray, spray drift or wash-off following rainfall events, and uptake via inhalation and absorption, (Figure 1), although there is little information available on this [80]. Secondary exposure is also possible through the ingestion of flora and fauna food sources containing glyphosate residues [52]. The risk of bioaccumulation through secondary exposure to glyphosate is known to be low, based on its low octanol-water partition co-efficient (logP Kow) (Table 2), well below the octanol-water partition co-efficient of 5.0 or greater suggested by Mackay and Fraser [81] as a threshold for the onset of bioaccumulation. In addition, studies have documented facile depuration via urine and faeces and a lack of significant residues accumulating in animal tissues [52,54]. In both these studies, glyphosate residues in the viscera, stomach contents and tissue samples of a range of small and large mammals were at or below concentrations found in ground cover and litter residues, indicating that glyphosate was not bioaccumulating in higher trophic levels.

Studies have generally reported minimal impacts from glyphosate applied under typical application rates in forests, on litter decomposition, soil microbial communities and soil microbial processes. Fletcher and Freedman [82] conducted laboratory studies with two leaf litter and one forest floor substrate and found that the threshold for glyphosate effects on litter decomposition was more than 50 times higher than residue concentrations that occur in the field after silvicultural herbicide treatments. In another laboratory study, Castilho et al. [83] found that a range of glyphosate products, applied at doses within the range used in managed forests, had no significant impact on microbial activity in forest soils. Soil DT_{50}'s in the forest field studies discussed in the 'Fate in litter and soils' section above, were at the low end of the range reported in Table 2. Peak glyphosate concentrations measured in planted forest litter and soils [51,52,54,57] were ~1 to 2 orders of magnitude lower than the LC_{50} for earthworms (Table 2). Edwards and Bohlen [84] also noted that glyphosate at exposures ranging from 1 to 100 ppm in soils had no toxic effects on earthworms. In Ontario, Canada, microbial processes and fungal community structures were unaffected by glyphosate (1.5 kg a.i. ha^{-1}) with only minor effects evident at the species level. In fact, soil type had a greater influence with microbial processes significantly higher in organic soils compared with mineral soils [85].

At experimentally higher application rates, glyphosate (3 kg a.i. ha^{-1}) manually applied over a 7–9 years period to *Pinus ponderosa* stands in California, USA, showed minimal effects on soil microbial communities over a range of soil types [86], where site productivity (characterised by site index) and seasonal factors had a greater influence on soil microbial community characteristics. These results concur with Durkin's [8] assessment that terrestrial microorganisms were unlikely to be adversely affected by glyphosate. However, Ohtonen et al. [87] examined microbial processes in a clear-cut forest in Ontario Canada, following annual glyphosate applications experimentally applied over a five year period and observed reduced microbial biomass carbon (C), microbial carbon, soil organic carbon ratio (Cmic/Corg), and decreased fungal biomass relative to bacterial biomass.

Field studies on the aquatic fate of glyphosate in managed forests (Table 3), indicate that the concentrations and duration of glyphosate typically measured, with the exception of direct over-spraying of wetlands [70], were well below the standard toxicity endpoints for fish and other aquatic organisms (Table 2) [71,88,89], often by orders of magnitude. In forest operational scenarios, the aquatic systems most likely to be over-sprayed are small shallow wetlands and low-order streams that are difficult to detect or avoid during aerial spray applications. Therefore the results of experimental over-spraying of these types of waterbodies as shown in Table 3 provide a surrogate measure of risk for this type of situation.

Amphibians, with their thin permeable skins, are potentially at risk from exposure to glyphosate [8]. In the case of Thompson et al. [70], the authors estimated an upper 99th centile glyphosate concentration of 0.55 ppm (550 μg L^{-1}) following chemical monitoring of directly over-sprayed wetlands in Ontario, Canada. Coincident biomonitoring showed no significant toxic effects on two species of sensitive amphibian larvae caged within the multiple wetlands under study. Furthermore, in situ enclosure field studies in either ponds in northern Ontario or in small wetlands in New Brunswick Canada, showed no significant effects on amphibian survival, growth or development when directly exposed to formulated glyphosate-based herbicides even at the maximum permissible label rates [77,78,90,91]. These results were similar to a field study in Oregon USA, assessing the effects of clear-cutting and clear-cutting followed by glyphosate application where no herbicide effects were observed for six species of amphibians [92].

Folmar et al. [89] noted that there was a potential risk to young-of-year fishes from glyphosate exposure in lentic bodies where dissolved oxygen levels are low or water temperatures are high, highlighting the sensitivity of these environments which lack the downstream dilution processes of running waters. In a comprehensive watershed level investigation on the effects of a glyphosate-based herbicide applied to a western Canadian coastal forest system [54,56], temporary stress effects and minor mortality (2.6%) were observed in caged coho salmon (*Oncorhynchus kisutch*) fingerlings held in an experimentally over-sprayed tributary and the main stream below the sprayed area in the immediate post-application period. However, no acute mortality, changes in over-winter mortality, growth rate or probability of using the tributary were observed for resident fingerlings [93].

Kreutzweiser et al. [94] also reported minimal effects on the drift patterns of stream insects in these streams. A New Zealand study also found no significant interactions between fine sediment and benthic invertebrates when exposed to glyphosate. Instead, sediment had a greater impact on a range of invertebrate indices compared with glyphosate concentration [95]. More recently, field monitoring studies conducted in Oregon showed that although multiple trace level detections of glyphosate were found in streams draining forested watersheds treated with glyphosate, cumulative time weighted exposure estimates resulted in a margin of safety approximating 100 fold for toxic effects on sensitive aquatic organisms [71]. As glyphosate salts and the free acid are highly water soluble, the risk of bioaccumulation in the aquatic environment is known to be very low (Table 2) [88] and in the Newton et al. [52] study, no glyphosate bioaccumulation was detected in coho salmon fingerlings.

As discussed, sediment sorption and degradation of glyphosate and associated surfactants has been identified as a primary removal mechanism for glyphosate from the water column in forested freshwater environments, a potential source of risk, particularly to sediment dwelling, organisms. However, these risks are tempered by the strong ionic sorption mechanisms which are considered to limit leaching or diffusion into the water column and bioavailability of sediment-bound residues [51,52,73,96], significantly reducing toxic effects. Nonetheless, experimental testing of sediment microbes exposed to environmentally relevant and high concentrations of glyphosate in lake sediments detected changes in community composition at glyphosate concentrations of 150 μg kg^{-1} dry weight [97] and laboratory tests by Tsui and Chu [98] found that sediment additions enhanced the acute or chronic toxicity of glyphosate-based formulations, particularly for filter-feeding organisms. In contrast, Wang et al. [96] found that sediment sorption reduced the toxicity of the surfactant polyethoxylated tallow amine (POEA), commonly used in glyphosate products and a primary toxicant for aquatic organisms, such as *Daphnia magna*. In wetland field studies, Baker et al. [99] showed a transient decline in plankton communities following coincident exposure to glyphosate and nutrients, but not glyphosate alone, suggesting that indirect or interactive effects with other stressors in aquatic communities are possible. These results highlight a need for further research on the potential indirect effects of glyphosate and surfactants which may be present in the sediments of aquatic environments for somewhat longer periods of time and particularly where such residues might interact with other stressors imposed by management of planted forests.

The field studies referred to in this review have assessed the environmental impact and risk of the entire formulated product. When exposed under laboratory conditions, fish and amphibian larvae are known to be highly sensitive to various surfactants such as POEA, which are included in most glyphosate-based herbicide formulations used in silviculture and that the expressed toxicity is also dependent upon pH, hardness and other characteristic of the aqueous medium, e.g., [8,72,89,98,100–102]. However, reviews by several authors on the potential environmental effects of formulated glyphosate products primarily used in North America [4–7,19], consistently conclude that the direct acute toxic effects to aquatic organisms are unlikely under realistic environmental exposure regimes in forests. This viewpoint is supported by the results of field studies on forest operational exposure to glyphosate products, as reviewed above, where significant direct toxic effects were not observed providing a posteriori support for the established threshold concentrations for glyphosate considered to be non-toxic for all aquatic life [88] (Table 4).

Table 4. Example water quality guidelines for glyphosate for the protection of freshwater aquatic environments.

Reference	Glyphosate Guideline
New Zealand's Environmental Risk Management Authority [103]	EEL [a] –0.37 mg a.i. L^{-1}
Australian and New Zealand guidelines for fresh and marine water quality [104]	Moderate reliability guideline figure (trigger value [b]) of 1200 μg a.i. L^{-1} for protection of 95% of freshwater species. For slightly-moderately disturbed systems the 99% protection value of 370 μg a.i. L^{-1} is recommended
Canadian Water Quality Guidelines for the Protection of Aquatic Life [88]	Long-term exposure [c] –800 μg a.i. L^{-1} Short-term exposure [d] –27,000 μg a.i. L^{-1}
	Short-term exposure [e] –0.250 (0.106–0.589) mg L^{-1}

South African water quality guidelines (SAWQGs) for Roundup (a.e. 360 g L^{-1}) [105]	Long-term exposure [f] −0.002 (0.000–0.021) mg L^{-1}
French Water Quality Guidelines [106]	Threshold value (PNEC) [g] −28 μg L^{-1} Max. acceptable concentration −70 μg L^{-1} Environmental quality guideline −0.1 μg L^{-1}

[a] An environmental exposure limit (EEL) establishes the maximum concentration of an ecotoxic substance, in this case glyphosate as the herbicidal active ingredient (a.i.), that is legally allowable in a particular environmental medium (e.g., water, soil or sediment). This includes the deposition of a substance onto surfaces (e.g., via spray drift); [b] glyphosate concentrations, if exceeded, would indicate a potential environmental problem and trigger a management response; [c] intended to protect all forms of aquatic life for indefinite exposure periods; [d] based on severe effects data for exposure periods of 24–96 h; [e] short-term lethal test ≤4 days; [f] long-term sublethal tests (≥4 days - ≤21 days) ; [g] PNEC = Predictable No-effect concentration.

4.2. Indirect Effects

Indirect effects of glyphosate to both terrestrial and aquatic fauna have been associated with changes in plant community composition, habitat structure, cover, and food sources and are primarily a consequence of glyphosate's phytotoxic effects rather than a result of ecotoxic qualities unique to the active ingredient [80,99,107–110]. Studies on small mammals (i.e., rodents, shrews, voles, chipmunks) showed that some short-term changes were observed at the species [111–113] and functional feeding group level [114], which the authors attributed to the reduction in invertebrates, plant cover and food. At the population level, glyphosate did not appear to have significant or long-lasting effects in the first few years after application [112,114,115]. Similar to small mammals, changes in bird community composition, and reductions in abundance, densities and species richness of bird populations often occurred in the first few years after glyphosate application [80,116–118], and in the case of Santillo et al. [117] the decline in bird densities was correlated with the decline in habitat complexity. These changes were assessed against untreated control sites to differentiate the effects of glyphosate from other background environmental factors such as the recovery trajectory following tree harvest and showed similar responses to other herbicides commonly used in managed forests [119]. Fewer studies are available on the indirect effects of glyphosate on terrestrial arthropods and results show a wide range of responses most likely in response to the organism's affiliation with and dependency on, habitat components affected by the glyphosate treatments [80]. Similarly, in aquatic systems, direct acute toxic effects are typically not observed at under realistic environmental exposure scenarios, however, indirect effects including restructuring of zooplankton and macroinvertebrate communities may occur if glyphosate-based herbicides are directly applied, for experimental purposes, at maximum label rates to small wetlands [99,107].

Less is known about the more subtle long-term indirect, synergistic and cumulative stressor effects of glyphosate in forested environments. Laboratory studies involving exposures to 58 and 116 μg L^{-1} glyphosate for 1 and 3 days have identified DNA damage in long-lived freshwater eels [120,121] and a New Zealand study found that the synergistic effects of glyphosate (exposure rate 360 μg L^{-1} for 26 days) and parasitic infections significantly affected the survival of a juvenile stage of native fish species (*Galaxias anomalus*) [122]. Further research is needed to assess the sub-lethal, long-term effects of glyphosate at rates used under forest operational conditions and to separate glyphosate effects from those of any other additives commonly used in forests.

In summary, toxicity results from laboratory and mesocosm studies on glyphosate products have rarely translated into similar toxic effects in the field when applied according to product label and best operational practices. As discussed, these results have been attributed to the rapid dissipation, sorption to soil, sediment and organic matrices, and microbial degradation processes in forested terrestrial and aquatic environments, reducing exposure time and duration for biological uptake of glyphosate and surfactants such as POEA. This outcome emphasises the need for a precautionary approach when extrapolating results from the laboratory to predict the effects and risks of glyphosate products on non-targeted organisms and environments in forested ecosystems. However, it should be noted that these results are based primarily on North American glyphosate-based products and information on the environmental effects of glyphosate-based products used in managed forests elsewhere is either minimal or absent [8].

5. Risk of Toxicological Effects on Humans

Many studies have been conducted to determine the potential for glyphosate and glyphosate-based herbicides to induce toxic effects in humans and these studies have been extensively reviewed by regulatory agencies and internationally renowned scientific experts repeatedly through time [1,4,5,8,18,23,24].

As specifically related to the issue of potential cancer risk, with the exception of the International Agency for Research on Cancer (IARC) [11] report, regulatory agencies around the world have all conducted multiple reviews and consistently concluded that registered uses of glyphosate in accordance with label directions do not pose a cancer risk, or any other risk, to human health [23–26,123,124]. The seeming contradiction between the IARC [11] conclusion and all others is largely explained by the fact that all other agencies consider carcinogenic risk potential in relation to potential realistic levels of human exposure, whereas the IARC process considers evidence for a potential hazard, without consideration of possible exposure magnitude or routes.

Despite the general consensus on human and mammalian toxicity and risk as summarized in the aforementioned professional reviews there are relatively fewer such assessments specific to human exposure and potential effects associated with glyphosate use in the planted forest sector. Durkin [5,8] presents a human health risk assessment relating specifically to glyphosate based herbicides as they are used in forest management by the US Forest Service. In these assessments, exposure for both workers and members of the general public were considered. Based on a standard unit application rate of 1.12 kg a.i. ha^{-1}, Durkin [8] concluded that general exposure for workers applying glyphosate either via manual, ground or aerial application was considered minimal. Even at the highest labelled application rate of 9 kg a.i. ha^{-1}, the risk of exposure of workers to levels of glyphosate above the RfD of 2 mg kg^{-1} day^{-1} was considered below a level of concern [8]. Similar studies to that conducted by Durkin [8] have shown that operator exposure to residues of glyphosate during routine manual applications has not resulted in levels of exposure that exceed even the newly proposed EFSA [23] Acceptable Operator Exposure Levels (AOELs) (Table 2) [18,125,126].

Manual application of glyphosate based herbicides using a knapsack sprayer is widely used in planted forests in South Africa and Chile for the control of competitive vegetation pre- and post-planting [27,33]. The studies cited above represent similar working conditions to that encountered by labourers who manually apply glyphosate based herbicides in field conditions during the establishment of young trees. While the specific exposure of forest workers to glyphosate in some regions has not been evaluated, it is likely their levels of exposure would be similar to those assessed by Durkin [5,8] and Dost [127] unless it could be shown there were significant differences in the rate of glyphosate applied (kg ha^{-1}), the area treated (ha) and the time period (number of months per year or number of years) over which workers were exposed to residues of the herbicide.

Significant exposure of the general public to glyphosate based herbicides applied to managed planted forests is generally unlikely and almost certainly less than for applicators as discussed above, given the: (1) infrequent use of glyphosate in any one forested area (once or twice in the rotation); (2) typical remote location of these plantations; (3) restricted public access in privately owned forests and general lack of a rationale for the public to enter these sites and (4) low probability of public entry within a few days of treatment when residues are at their highest levels and when they are more likely to dislodge from treated surfaces.

In cases where the general public do enter treated sites shortly after treatment, potential routes of exposure could include ingestion of contaminated surface water, dermal sorption of residues dislodged from plant surfaces and/or ingestion of contaminated plants such as wild berries, mushrooms and other species commonly used as natural food sources. In their review of glyphosate the Canadian Pest Management Regulatory Agency [24] concluded that non-occupational risks from bystander dermal exposure when glyphosate was used according to label rates was not a concern. This outcome included the consumption of wild food (berries, birds, small and large mammals) that may be present in planted forests. In support of this conclusion, studies by Newton et al. [52], Couture et al. [21] and Durkin [5] indicated that there is no route of exposure or exposure scenario suggesting that the general public will be at risk from longer-term exposure to glyphosate under typical use conditions in planted forests vegetation management. Similarly, Legris and Couture [54], found no measureable residues in 31/32 edible tissue samples taken from hares (*Lepus americanus*), moose (*Alcesalces*) and deer (*Odocoileus virginianus*) sampled from territories within glyphosate treated spray sites.

However, Durkin [8], identified consumption of contaminated water after an accidental spill as an (acute) exposure scenario that could reach, but not exceed, a level of concern for the general public. This same author also identified the only non-accidental exposure scenario of concern as the consumption of contaminated vegetation shortly after glyphosate is applied, particularly when applied at rates above 1.6 kg a.i. ha^{-1}. These potentially higher risk scenarios, both manageable, represent the only examples that could be of concern to forest managers. However, given the use patterns in forest management, the rapid degradation of this active ingredient, the phytotoxicity to fruit bearing shrubs (i.e., berries and plants dead in 4 to 6 weeks) and the ability to mitigate this risk through restriction of public access, we support the general contention that it is likely consumption of wild food is a low risk pathway for human exposure to glyphosate in the planted forest environment.

In forested catchments, the exposure of humans (and terrestrial fauna) to high levels of glyphosate in forest streams through consumption of contaminated surface waters is unlikely given the low risk of movement of glyphosate into stream water sources following application in planted forests, coupled with rapid degradation and dilution downstream, as described in Section 3. Moreover, there is no evidence that the use of glyphosate in forested catchments has resulted in levels of glyphosate in water bodies likely to exceed human health and drinking water standards (Section 4; Table 3). In forest soils, glyphosate is rarely detected below the upper 15 cm level of soils [51,52,57,60,61], indicating that it is very unlikely to percolate down through forest soils and into groundwater. Given that in forestry scenarios glyphosate use is much less frequent than that in agricultural situations the risk to humans from water consumption is low. In fact, forest are recognised globally for their importance in providing sources of high water quality drinking water [128,129].

In New Zealand, although herbicides are the most commonly detected pesticide in national surveys of groundwater, no glyphosate has yet been detected [130] despite the relatively high dependence on this active ingredient in agriculture and across primary industry [37]. Vereecken [22] reported on several studies in European agriculture that showed low level residues occurring infrequently in groundwater with no detections above drinking water standards in Denmark, the United Kingdom, the Netherlands or Norway. In a comprehensive assessment of the fate of glyphosate and AMPA in the USA, Battaglin et al. [131] found that both products were frequently detected in rivers and streams, less so in lakes and ponds and infrequently in groundwater. The author's noted that most glyphosate concentrations were below existing health benchmarks and levels of concern for humans. Similarly, a multi-year study of pesticide residues in four rivers in an agricultural region of southern Quebec showed the maximal concentrations of glyphosate ranging from 3.3 to 29.0 ppb [132]. Even maximum levels observed in these agricultural scenarios are far below the maximum acceptable concentration of 280 ppb established by Health Canada as protective of human health assuming a lifetime (70 years consumption) of 1.5 L of drinking water per day [133].

6. Best Management Practices and Mitigation of Risks

For many years, foresters have been proactive in increasing the efficiency and decreasing the potential for non-target effects associated with herbicides use in forest management [134,135]. This trend was accelerated in the late 1990s through adoption of third party certification programmes by many forest companies. Such certification systems include those of the Forest Stewardship Council (FSC) and those under the umbrella of the Programme for the Endorsement of Forest Certification (PEFC). Although originally established to reduce trade in illegally logged timber, certification also aimed to provide consumers with assurance that wood products were derived from sustainably managed forests. As such, responsible use of pesticides is often a key certification requirement [136,137]. That nearly 500 million hectares of forests worldwide are certified with either FSC or PEFC indicates that the forest industry strives towards sustainable (economic, environmental and social) management of their resources [138,139].

In most forest growing regions of the world, forest management operations are planned in detail with strict self-regulation and also control by various government agencies [135,140–142]. Regulations, forest management planning and best practice guidelines related to herbicide use are good examples of the level of planning, regulation and control imposed. Herbicide product labels represent legal documents and are required by law to be applied in strict accordance with instructions specified therein. In most countries with major use in production forestry and where modern techniques are employed, applications are made only by specifically and formally trained personnel [135,141,143]. Where aerial applications are involved, extensive regulations and forest industry best management practices typically include requirements to: (1) use fully calibrated aircraft and dispersal systems; (2) employ electronic guidance systems to guide, track and provide spatially explicit archival data characterizing the operation; (3) minimize off-target drift of the spray cloud following release through constraints imposed on aircraft speed, release height, droplet size, nozzle configuration, maximum rotor ratios and wind speed; (4) retention of protective buffers, or 'no-spray' zones to protect watercourses, riparian zones and other sensitive areas [35,74,135,140]. Field studies have confirmed that vegetated buffers significantly mitigate against glyphosate exposure minimising the potential for adverse effects of glyphosate on non-target environments under typical aerial spray operations [21,54,70,74,76]. Based on validated drift modelling results, the amount of glyphosate depositing at distances of 25 to 65 m downwind of the spray block edge have been estimated to be between 2% and 5.6% of the full application rate [135,144]. Newer formulations of glyphosate that are rainfast within hours of application will also reduce the potential for contamination of surface water should rainfall and run-off occur within the 24 h of application [145].

With respect to mitigating against potential accidental human exposures most countries require direct mapping and notification of nearby residents prior to the initiation of the spray program (ground or aerial), signage of the specific areas before and after treatment and reconnaissance of the site and/or controlled access to the sites immediately prior to and after treatment are made. Persons most likely to have any level of exposure are those directly involved in mixing, loading or application of herbicides and are typically required to use personal protective equipment (PPE) as a means of reducing or eliminating their exposure. [31,35,66,135,140,142,146].

7. Conclusions

Scientific studies spanning more than four decades of glyphosate use for forest vegetation management across the globe indicate a general lack of significant deleterious effects to humans, terrestrial and aquatic fauna, and environmental quality. With specific reference to operational control of weeds in planted forests, glyphosate-based herbicides are the dominant products in use internationally. In the forest sector, these are used judiciously and infrequently (once or twice per rotation), at rates generally not exceeding 4 kg ha^{-1}, within legal label recommendations and typically by highly trained applicators in accordance with numerous regulatory controls and best practice guidelines.

There are few, if any, alternatives either chemical or non-chemical available to foresters that can match glyphosate based herbicides in terms of their relatively low cost, systemic effectiveness, spectrum of activity against key competing plant species, favourable environmental fate, ecotoxicological and human risk profiles. It is likely that any alternative treatment would require a mix of active ingredients for which there is minimal scientific knowledge upon which to similarly assess potential risks, as well as predictably poorer outcomes in the context of overall cost/benefit.

In terms of human exposure to glyphosate during operational application in planted forest management, those with greatest potential exposure include those involved in manual application (e.g., backpack spray applicators) or in mixing/loading of either ground-based or aerial spray equipment. However, professional risk assessments demonstrate that when applied according to label recommendations for forest vegetation management, the risk of exposure to levels that exceed the accepted No Observable Effect Level (NOEL) or Acceptable Daily Intake (ADI) are likely low. A study to confirm these observations for contract labour seasonally exposed to glyphosate residues over periods extending several months to years may be required in regions where manual application of glyphosate is the only method employed. However, all studies to date on worker exposure indicate no significant risk to human health. In New Zealand, Australia, Canada and the USA, the near exclusive application of glyphosate-based herbicides from aircraft, using modern mixing/loading technologies and appropriate personal protective equipment substantially reduces the potential for exposure and thus risk to personnel directly involved in these operations.

Assessment of the available literature on the direct and indirect risks of glyphosate-based herbicides applied to the forest environment under operational conditions revealed no significant adverse effects to terrestrial and aquatic fauna. However, the tendency for glyphosate and surfactants to bind in sediments, and the limited information on the impact to sediment interactive organisms represents another possible area for further research. In addition, the subtle, sub-lethal, long-term, indirect effects, or potential interactions of glyphosate-based herbicides with other environmentally relevant stressors (e.g., herbicide mixtures, low dissolved oxygen, pH, excess nutrient inputs, other chemical pollutants) are less well understood as compared to simple direct acute or chronic effects. Future research, based on probability of coincident occurrence of such multiple stressors in the forest sector and the size of area to which such results would pertain could be recommended as a means of prioritizing future research on these aspects.

It should be recognised that most of the studies cited in this review were heavily focused on glyphosate products used in North American forests, with minimal or no information on the environmental fate, and effects of glyphosate-based products, in planted forests of other regions of the world with differing tree species, silvicultural regimes, and environmental conditions (i.e., climate, soil etc.). While this could represent a gap in the data available to reliably assess the risk to the planted forest environment of glyphosate based herbicides, there are few reasons to expect significantly different outcomes, barring identification of more sensitive species than those studied to date, drastically different environmental characteristics or new formulations or mixes that incorporate components with higher inherent toxicity.

Few countries have reliable up-to-date systems, as practiced in Canada, for tracking pesticide use across primary industry, including that for forest management. A lack of data renders industries vulnerable to public enquiry and unable to demonstrate actual herbicide use (rates, active ingredients and total amounts applied), or changes in practice/trends of active ingredient usage over time, a factor which can reliably demonstrate a sector's commitment to responsible use of herbicides. More robust tracking of herbicide use at a national scale by all primary industries should be a consideration for all regions heavily dependent on chemicals for vegetation or weed control.

Public concerns over the use of glyphosate-based herbicides continue, and show evidence of increasing. Such concerns, in spite of the weight of scientific evidence available, have the potential to deleteriously impact management of planted forests internationally. Often, the global concerns over the use of glyphosate-based herbicides are intertwined with broader issues of land management or opposition to "big business" with toxicological and eco-toxicological issues aside. Avoiding this potentiality requires a concerted effort by scientists, forest managers, extension specialists and regulators alike to ensure enhanced communication systems (i.e., as in forestinfo.ca_website) that extend to the public and decision makers such that decisions are made on a scientific rather than an unsupported public perspective basis. In this regard, the aim of this review was to synthesize relevant science relating to use of glyphosate-based herbicides in the forest sector. While it is certainly true that additional research on some topic areas is required, it is equally true that most of the priority questions and particularly the common misperceptions that routinely circulate through the Internet have been directly addressed by scientific investigations. The weight of available scientific evidence contained in this extensive scientific knowledge base leads to the conclusion that glyphosate-based herbicides as typically employed in planted forest management do not pose a significant risk to humans, the environment or wildlife species associated therewith. The general congruence of this conclusion as drawn from this review, with that derived from numerous other independent scientific reviews and regulatory risk assessments across the globe, provides a substantial level of confidence in the validity of this general conclusion.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix

Table A1. List of products containing glyphosate commonly used in planted forest management in Australia, USA, Canada, Chile, New Zealand and South Africa.

Product	Concentration of Glyphosate and Form in Which It Occurs in the Herbicide Product	Country	Manufacturer
Glymac™ Dry 700	700 g/kg glyphosate (monoammoium salt)	Australia	Macspread Pty Ltd.
Glymount 450	450 g/L glyphosate (isopropylamine salt)	Australia	Growchoice Pty Ltd.
Glyphosate 450 CT	450 g/L (isopropylamine salt)	Australia	Nufarm
MacPhersons Bi Dri 700	700 g/kg glyphosate (mono-ammonium salt)	Australia	Mac Phersons
Redox 450	450 g/L glyphosate (isopropylamine salt)	Australia	Redox
Round-up Attack	570 g/L glyphosate (potassium salt)	Australia	Nufarm
Roundup Biactive	360 g/L glyphosate (isopropylamine salt)	Australia	Sinochem International
Weedmaster Duo	360 g/L glyphosate (isopropylamine salt & monoammonium salt)	Australia	Nufarm
Panzer® Gold	484 g/L glyphosate	Chile	Dow AgroSciences
Rango Full	540 g/L glyphosate	Chile	
Mamba DMA 480 SL L8388	480 g/L glyphosate (dimethylamine salt)	South Africa	Dow AgroSciences
Glygran 710 SG L8449	710 g/kg glyphosate (ammonium salt)	South Africa	Villa Crop Protection
Roundup max L6790	680 g/kg glyphosate (ammonium salt)	South Africa	Monsanto SA
Glyphogan 360 SL L5393	360 g/L glyphosate (isopropylamine salt)	South Africa	Makhteshim-Agan
Sharda Glyphosate 360 SL L8901	360 g/L glyphosate (isopropylamine salt)	South Africa	Sharda International Africa cc.
Kalach 510 SL L8311	510 g/kg glyphosate (isopropylamine salt)	South Africa	ArystaLifeScience
Mamba Max 480 SL L7714	480 g /kg glyphosate (isopropylamine salt)	South Africa	Dow AgroSciences
Erase L6206	360 g/L glyphosate (isopropylaminesalt)	South Africa	Plaaskem
Tumbleweed L4781	240 g/L glyphosate (isopropylammonium salt)	South Africa	Enviro Weed Control Systems
Mamba 360 SL L4817	360 g/Lglyphosate (isopropylamine salt)	South Africa	Dow AgroSciences
Roundup L0407	360 g /Lglyphosate (isopropylamine salt)	South Africa	Monsanto SA
Springbok 360 L6719	360 g/L glyphosate (isopropylamine salt)	South Africa	ArystaLifeScience
Kilo Max 700 WSG L8310	700 g/L glyphosate (sodium salt)	South Africa	ArystaLifeScience
Bounty 500 WSG L6698	500 g/Kg glyphosate (sodium salt)	South Africa	Meridian Agritech
Erase Granule L7948	500 g/Kg glyphosate (sodium salt)	South Africa	Plaaskem
Muscle-Up 500 SG L7641	500 g/Kg glyphosate (sodium salt)	South Africa	Ag-Chem Africa
Glyphosate WSG L7119	500 g/L glyphosate (sodium salt)	South Africa	ArystaLifeScience
Slash Plus 540 SL L8819	540 g/L glyphosate (potassium salt)	South Africa	Universal Crop Protection
Roundup Turbo L7166	450 g/L glyphosate (potassium salt)	South Africa	Monsanto SA
Riverdale Razor Herbide	356 g/L glyphosate(isopropylamine salt)	USA	Nufarm Americas Inc.
Razor pro	356 g/L glyphosate (isopropylamine salt)	USA	Nufarm Americas Inc.
Glyphosate 4 Plus	356 g /L glyphosate (isopropylamine salt)	USA	Alligare, LLC
Glyphosate 5.4	480 g/L glyphosate (isopropylamine salt)	USA	Alligare, LLC
Accord	480 g /L glyphosate (isopropylamine salt)	USA	Dow AgroSciences
Accord XRT	480 g/L glyphosate (isopropylamine salt)	USA	Dow AgroSciences
Accord XRT II	480 g/L glyphosate (isopropylamine salt)	USA	Dow AgroSciences
Foresters	480 g/L glyphosate (isopropylamine salt)	USA	NuFarmAmercica Inc.
One step	76 g/L glyphosate (isopropylamine salt)	USA	BASF
Refuge	599 g/L glyphosate (monopotasium salt)	USA	Syngenta
Rodeo	480 g/L glyphosate (isopropylamine salt)	USA	Dow AgroSciences
AGPRO Glyphosate 360	360 g/L glyphosate (isopropylamine salt)	New Zealand	AGPRO

Deal 510	510 g/L glyphosate (isopropylamine salt)	New Zealand	Orion
AGPRO Glyphosate 360	360 g/L glyphosate (isopropylamine salt)	New Zealand	AGPRO
Weedmaster® Dry	680 g/kg glyphosate (monoammonium salt)	New Zealand	Nufarm
AGPRO Green Glyphosate 510	510 g/L glyphosate (isopropylamine salt)	New Zealand	AGPRO
Vision Silvicultural Herbicide	356 g/L glyphosate (isopropylamine salt)	Canada	Monsanto Canada Inc.
Vision Max	540 g/L glyphosate (potassium salt)	Canada	Monsanto Canada Inc.
Forza™	360 g/L glyphosate (isopropylamine salt)	Canada	Cheminova Canada Inc.
Vantage Forestry Herbicide Solution	410 g/L glyphosate (isopropylamine salt)	Canada	Dow AgroSciences

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