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Review Article

Environmental Benefits and Risks of Herbicides Use in Forestry – Review

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Abstract

The use of herbicides in forests is important for enhancing tree growth and forest productivity. By effectively controlling competing vegetation, herbicides facilitate the survival and healthy development of young trees. They also play a key role in efficient forest management, contributing to the sustainability and economic viability of forestry practices. This effective vegetation management is crucial for meeting global demands for wood and forest products. This comprehensive review critically examines the dualistic nature of herbicide use in forestry, exploring both its environmental benefits and risks. The paper delves into the historical evolution of herbicide technology in forest management, highlighting its significant role in enhancing tree growth and wood volume yields. With a focus on long-term studies it is analysis the efficacy of herbicides in improving forest productivity and their compatibility with environmental sustainability. The review also addresses the contentious debate surrounding herbicide use, particularly its perceived threats to biodiversity conservation and wildlife management. Additionally, we explore alternative vegetation management strategies, including biological control methods like Mycoherbicides, and discuss emerging trends in sustainable forest management. The paper aims to provide a balanced understanding of the interplay between economic benefits and ecological imperatives in modern forestry, emphasizing the need for a nuanced approach to herbicide use. Through this exploration, the review contributes to the discourse on harmonizing forest management practices with environmental stewardship.

Keywords: Herbicides in Forestry, Sustainable Forestry Practices, Environmental Impact of Herbicides, Mycoherbicides, Forest Management and Sustainability.

INTRODUCTION

The employment of herbicides in forestry encompasses both environmental benefits and inherent risks. On one hand, herbicides contribute to forest health by controlling invasive and competitive species, thus promoting the growth of planted trees and contributing to overall forest productivity. They also aid in reducing soil erosion by limiting the need for mechanical ground disturbance. Conversely, the ecological risks of herbicides, including potential toxicity to non-target species, contamination of water sources, and the disruption of forest ecosystems, warrant careful consideration. The challenge lies in executing a balanced approach that leverages the ecological advantages of herbicides while mitigating their risks through strategic, informed application and the integration of sustainable forestry practices. The single significant treatment impacting tree growth and survival, and consequently crop productivity, involves the management of competing vegetation during the development of forests planted for the production of lumber or fiber (Wagner *et al.*, 2006). Herbicides are a very good way to guarantee regeneration investments (Pitt *et al.*, 2004, Wagner *et al.*, 2006). Herbicide use can boost wood volume yields in young forests by 50-150% when used to suppress competing plants (Guynn *et al.*, 2004). Herbicide use is steadily rising for controlling invasive plants, altering wildlife habitats, and managing timber on commercial pine (*Pinus* spp.) plantations (Miller *et al.*, 2004). Over the past 60 years, forest management has changed, and herbicide technology has advanced to become a crucial component of contemporary forestry practices. Herbicides have been recommended by forest managers in an effort to boost long-term timber production and the success of replanting. However, the use of herbicides has frequently been seen as incompatible with the goals of wildlife managers and other stakeholders involved in biodiversity conservation. Are herbicides suitable with the goals of biodiversity conservation and animal management, and do they boost forest productivity? The total amount of wood volume yield obtains from efficiently managing forest vegetation (mainly using herbicides) is estimated to be 30–450% in Pacific Northwest forests, 10–150% in southeastern forests, and 50–450% in northern forests, according to the findings of the longest-term studies (10-30 years) conducted in all over the world. The majority of the 23 studies that were looked at showed advances in wood volume yield for key commercial tree species of between 30 and 300 percent, and those gains were very stable for a variety of site conditions. The increasing demand for wood from society on a decreasing amount of forestland will need to be met in order to meet future demands for biodiversity protection and wildlife habitat. Part of the answer will be increased fiber yields from plants under intensive management, which involves the use of herbicides (Wagner *et al.,* 2004). This analysis offers an exhaustive evaluation of the diverse consequences of herbicide application in forestry sectors, with a particular focus on their role in augmenting wood yield. The examination of long-term studies provides insights into the reliability of yield enhancements across various environmental conditions. The discourse extends to reconcile the rising demand for sustainably sourced lumber with the need to conserve biodiversity and wildlife habitats. The critical function of herbicides in high-intensity forest management is highlighted, promoting a dialogue on aligning forestry's economic goals with environmental responsibilities. This review critically assesses the complex role of herbicides, from their historical development to their contentious position within the broader objectives of ecological conservation.

Role of Herbicides in Forestry

Over the past 50 years, competing vegetation management has changed along with forest management and is now a crucial component of contemporary forestry practice in many regions of the world. Establishing high-yield forest plantations has shown to be particularly dependent on effective vegetation management, mostly through the use of herbicides. Over the last few decades, a significant amount of study has been done to quantify the increases in wood yield that result from managing competing vegetation (Wagner *et al*., 2006).

In order to increase productivity, forest management must become more intensive due to the growing demand for forest products. In densely managed forests, competing vegetation interference will remain a significant issue, necessitating increased focus on vegetation management to maximize the conversion of forest resources into commercial goods (Pabst *et al*., 1990). The management of forest vegetation has changed significantly over the last few decades. The demand for greater production has prompted these changes, which have also been brought about by new technologies-chemical herbicides, in particular, and technology for clearing forests and preparing sites. There have been weed issues associated with every stage of forest management history, and many of the measures that followed were intended to address these issues (Smithers, 1964). Certain sites acquired dense understories of shade-tolerant brush species, or degraded into low-value hardwoods under partial cutting schemes where mechanization was limited and horses and manual power predominated (Post, 1969). Large-scale clear-cutting was made possible by mechanization, which frequently resulted in the eradication of advance regeneration and the quick emergence of not for profit pioneer species. In many places, efforts to eradicate this vegetation using mechanical or incendiary site preparation techniques were effective; but, in other places, similar treatments accelerated the resurgence of weed species from windblown or buried seeds or through accidental sprouting from stumps or rhizomes (Oswald, 1990).

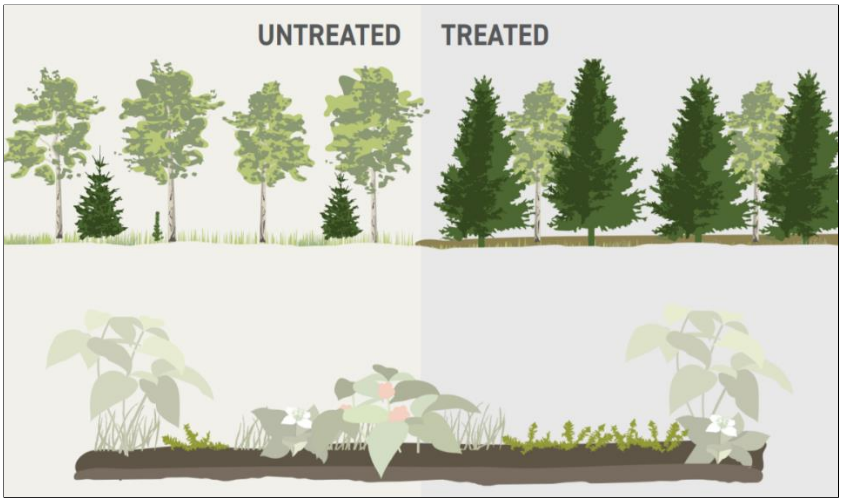

Figure 1: Effects and ecological impact of herbicides in forest management (YourForest, 2021)

Chemical herbicides have been used more frequently, along with the use of fire and large machinery (Campbell, 1990). These are usually useful instruments for controlling undesirable plants, but because to possible negative impacts on ecosystems, public opposition to their use, and ensuing political issues, a large portion of their potential may remain unrealized. Herbicides and other pesticides have been used in agriculture to feed the world's expanding population, but due to the same worries, there will likely be a decrease in the usage of chemicals, which will make it unlikely that better chemicals will be created and approved. Since most forests are located on public land and non-timber values such as wildlife, fisheries, and rare or endangered species are becoming more and more important, there may be more limits on the use of pesticides in forestry. The risk of removal of current products is rising while the probability of registering novel chemicals for use in forestry are progressively declining (Halleran, 1990). It is obvious that we must look for substitutes for the methods of vegetation control we already used. Biological control, or the intentional employment of natural enemies to stifle the growth or lower the number of instances of a weed species, is a significant substitute (Watson, 1989). In biological control, there are three main approaches: the standard or inoculative approach, which involves importing and releasing exotic bio control agents; the inundative or bioherbicide approach, which involves mass-cultivating or rearing bio control agents and applying them to target weeds; and the augmentative or integrated plant management approach, which involves manipulating natural populations of pests or pathogens of weeds (Templeton, 1990).

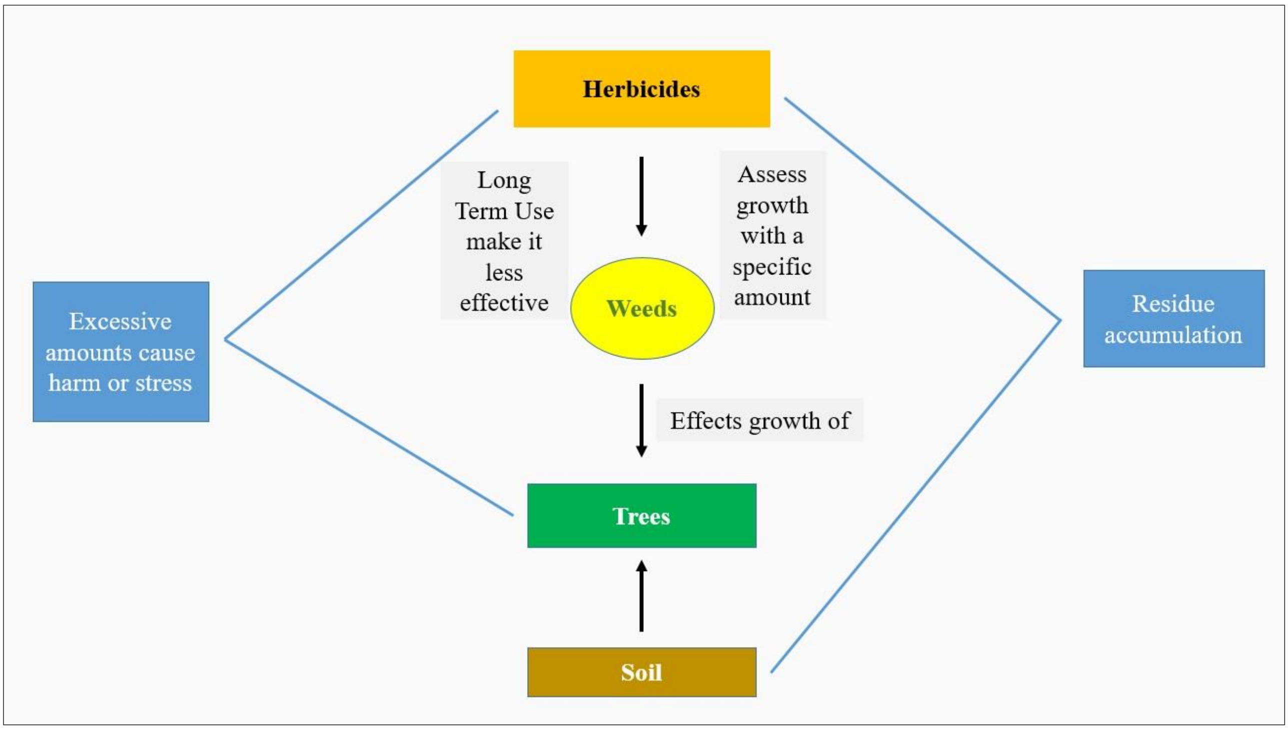

Figure 2: Impact of Herbicide Use on Weeds, Trees, and Soil Ecosystems

Mycoherbicides

Mycoherbicides are solutions that are sprayed directly to the target weeds and contain plant pathogenic fungus. Mycoherbicides have just lately been utilised in operations, beginning in the 1980s (TeBeest and Templeton 1985). Nonetheless, the concept is nearly as old as plant pathology, with studies of disease impacts on weeds being documented as early as the eighteenth century (Wilson 1969). Persimmon and scrub oak trees were among the weed trees used in some of the first mycoherbicide trials (French and Schroeder 1969). Currently, the usual rule for developing mycoherbicides is to exclusively use organisms that are native to the areas where the particular target weeds are problematic (Anonymous 1990). Biotechnology may one day be utilized to enhance pathogens for the purpose of controlling weeds. To increase the effectiveness of fungi as mycoherbicides, even traditional selection and breeding methods may be used; fungus may be created with increased host selectivity, pathogenicity, or decreased capacity for natural survival (Sands *et al.*, 1990).

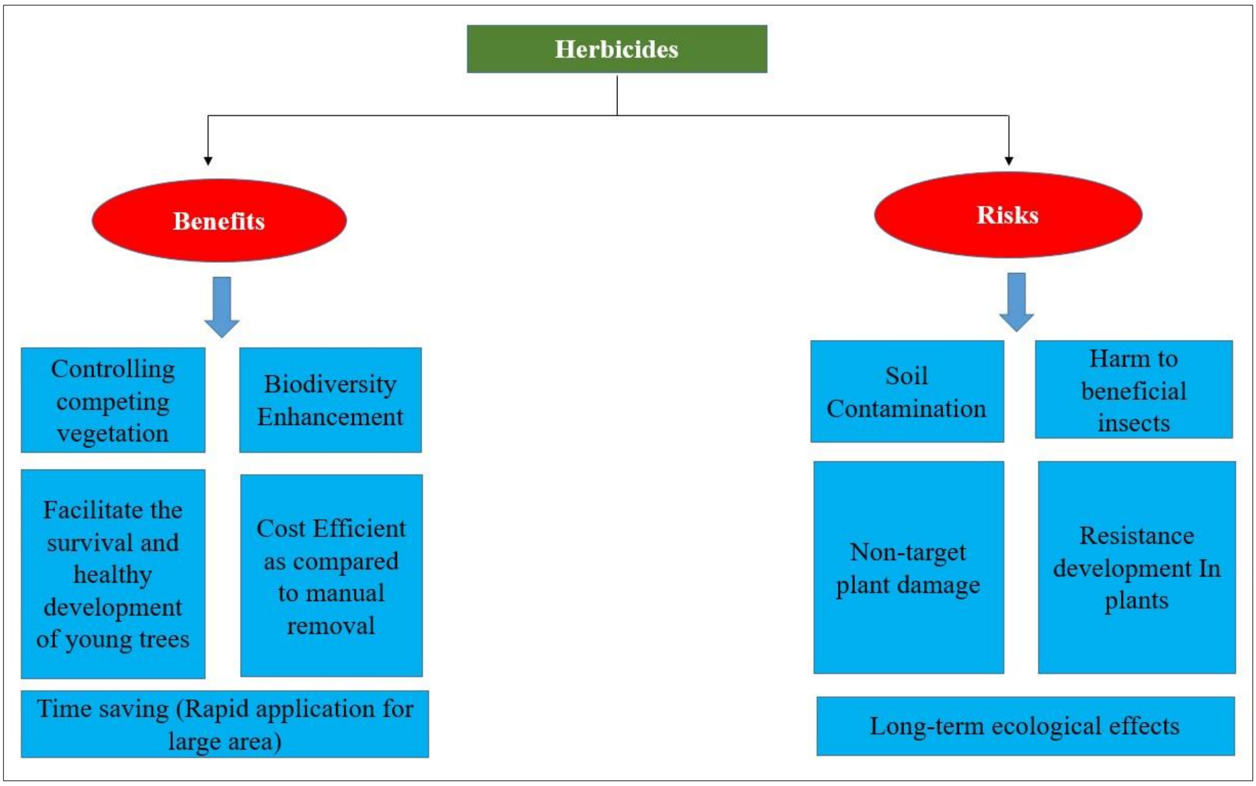

Figure 3: Balancing the Scales: Benefits and Risks of Herbicide Use in Forestry

Environmental Benefits of Herbicides Use

Sedimentation is the main issue with water quality worldwide. Herbicide usage during stand development to suppress competing plants can improve water quality and the sustainability of forest ecosystems by minimising soil loss from off-site, lowering soil and organic matter displacement on-site, and halting the deterioration of soil physical qualities. The natural losses of sediment from intact watersheds can be 1-2 orders of magnitude smaller than those from places where competing vegetation is managed by mechanical means. Vegetation management approaches generally result in a ~7% annual raise in erosion on a watershed basis. Herbicides don't speed up erosion that occurs naturally. Essential organic matter and nutrients for the long-term productivity of the site can be removed off-site by fire and mechanical vegetation methods of management, or they can be reallocated on-site in a way that decreases availability to the following stand. The destiny of herbicides used in forestry in different watersheds across the southern and western United States, Canada, and Australia has been studied for a number of decades. Chemicals like 2,4-D, glyphosate, hexazinone, imazapyr, metsulfuron, picloram, sulfometuron, tebuthiuron, and triclopyr have all been tested in this study. Evaluations have been done on leaching to groundwater and streamflow losses. According to data from field studies, residue concentrations are often modest and don't last for very long-that is, unless direct applications are made to transient channels or streams. The US regional environmental impact assessments show that the presence of forestry herbicides in groundwater and surface water poses little threat to public health or water quality. Additionally, they show that herbicides can significantly lessen the deterioration of water quality caused by sedimentation and erosion. (Neary *et al.*, 1996).

We review the environmental fate and toxicity data for three substances that seem promising for vegetation control in forestry: 3-cyclohexyl-6-(dimethylamino)-1-methyl-1,3,5-triazine-2,4(1H, 3H)-dione [hexazinone], N- (phosphonomethyl) glycine [glyphosate], and ammonium ethyl carbamoylphosphonate [fosamine ammonium]. With half-lives of roughly 7-10 days for fosamine ammonium, 8-19 weeks for glyphosate, and 1-6 months for hexazinone, according to soil type and climatic circumstances, none of the three herbicides is very persistent in soil. Microbial pathways account for the majority of degradation in soil. In contrast to glyphosate and fosamine ammonium, which are highly adsorbed and not easily absorbed in many soil types, hexazinone is a fairly mobile herbicide, with mobility varying according to soil type. The bioassay results indicate that the toxicity of the three herbicides ranges from very low to low. When given at 10,000 parts per million to pregnant rats, fosamine ammonium did not cause teratogenicity or mutagenesis. Data regarding hexazinone show that it has no cancerous effect on rats, is not teratogenic or embryotoxic at concentrations up to 5000 ppm in the diet of rats, and is negative in assays for bacterial and mammalian point mutations. The three herbicides show little to no potential for biological accumulation and have little to no impact on soil microorganisms. There is a discussion of the limitations of the current data and recommendations are offered for further research (Ghassemi *et al.*, 1982).

Environmental Risks of Herbicides Use

In forestry, herbicides are used to eliminate invasive exotics, modify wildlife habitat, lessen competition from shrubs and herbaceous vegetation, and manage the composition of tree species. The amount of herbicides used in forestry is not reflected in national figures. 51 different applications of 1-3 herbicides were utilized, and 11 applications (with 6 active ingredients) accounted for 90% of the area allegedly treated, according to a survey of 13 forest products businesses. Average rates varied from 10-42% of the labelled maxima, while reported rates were consistently lower than the maximum labelled rate. In 2001, 74,464 hectares of the National Forest System, including grassland, were treated with herbicides. In 2002, 985,237 hectares were treated according to a second survey on the use of forestry herbicides across all ownerships. The toxicity of herbicides to people, pets, cattle, and wildlife as well as their effects on wildlife habitat are among the public's concerns regarding their use in forests. The Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) controls the usage and sale of herbicides and offers a thorough system of toxicity assessment. FIFRA testing raises some issues, though, because it only tests the active chemicals of herbicides and does not test the combinations of herbicides that are frequently used in forestry. It also uses a limited number of sentinel species. A permit under the Clean Water Act (CWA) is necessary for the aerial spraying of pesticides, including herbicides, as it is believed to be a point-source discharge of pollutants into US waters based on recent litigation. Due to the confusion these lawsuits have caused regarding the relationship between two federal legislations (FIFRA and CWA) and pesticides, new policy clarification is currently being drafted. A procedure to enhance federal agency consultation on pesticides' potential to harm vulnerable and endangered species has been sparked by other lawsuits. In conclusion, herbicides can be used to regulate the habitat of wildlife and are essential for the management of commercial timber. Herbicide usage in forestry poses little harm to people or wildlife, according to federal laws and water quality monitoring (Shepard *et al.*, 2004). Less than 0.1% of insecticides used to eradicate pests really get to the intended targets. Therefore, over 99.9% of pesticides that are used end up in the environment, contaminating soil, water, and the ecosystem's atmosphere while also having a negative impact on beneficial biota and public health. By protecting the ecosystem and public health, improved pesticide application technology can increase the effectiveness of pesticide use (Pimentel, 1995).

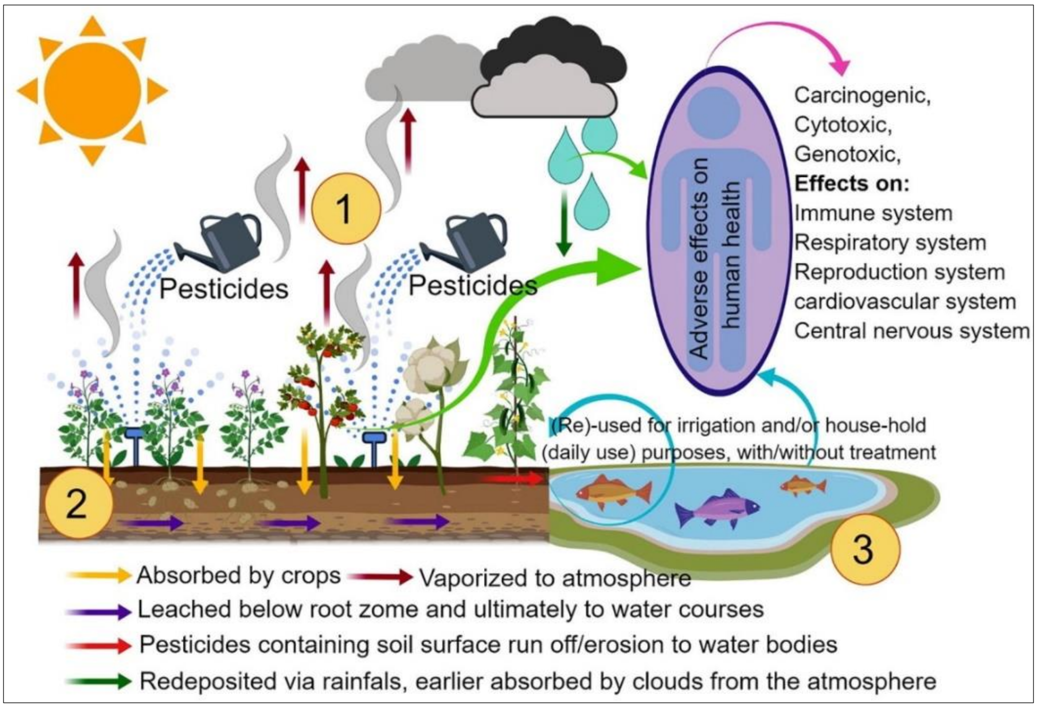

Figure 4: Adverse effects of herbicides and pesticides on environment. (Liu *et al.*, 2019)

Herbicides use in forests is trending downward globally (Thompson and Pitt 2003; Little *et al.*, 2006; McCarthy *et al.*, 2011). Environmental policies implemented at the national or regional levels, along with forest growers' voluntary participation in independent forest certification programmes like the Forest Stewardship Council (FSC) or the Programme for the Endorsement of Forest Certification (PEFC), are driving pressure to move away from herbicides. These certification programmes support sustainable forest management techniques and frequently include a reduction or even elimination of the use of herbicides

(Forest Stewardship Council, 2007; Wilson, 2012). Because of its low toxicity, long-lasting effects, and affordability, glyphosate has been widely used to control forest weeds as a result of this mandate. (Willoughby *et al.*, 2009; Thompson and Pitt, 2003). Herbicide use in forest plantings is under pressure to decrease due to environmental concerns about off-site migration and the harmful impacts of herbicides on surface and groundwater quality. But it crucial to take into account both the context of herbicide use and the consequences of alternative management strategies used to accomplish the same aim when discussing the possible environmental hazards linked to these pesticides. For instance, when applied properly, herbicides can reduce impacts on water quality, site productivity, and forest sustainability because they don't have the negative consequences of catastrophic fires and mechanical site preparation (Neary and Michael 1996). One could argue that by keeping nutrient-rich organic material and soil-surface horizons on the location, herbicide applications help to preserve site productivity and protect the integrity of the water (Neary and Michael, 1996).

The main grounds for public objection to herbicide use in forests are usually worries about possible toxicity to wildlife. Understanding the toxicity of herbicides as well as their environmental fate and movement is necessary to characterize the risk that wildlife poses from silvicultural herbicides. The types and timing of organism exposures are determined by the chemistry and fate of herbicide and supplements in environmental media. The types of organisms or life stages that may be most vulnerable to harmful effects and appropriate exposure levels and durations are determined by the toxicity of herbicides, adjuvants, and their breakdown products as well as the levels at which those toxic responses may be observed. Herbicides such as glyphosate, triclopyr, imazapyr, sulfometuron, metsulfuron methyl, and hexazinone, which are frequently used in forestry to control vegetation, generally break down rapidly in the environment and are therefore neither permanent nor bioaccumulative. Modern herbicides have a minimal level of direct toxicity to animals since they are made to target the metabolic processes that are specific to plants. Current silvicultural herbicides present little risk to wildlife when used in accordance with label directions (Tatum, 2004).

Glyphosate

In 1974, Monsanto launched glyphosate (CAS 1071-836) on the market as a non-selective, wide-spectrum post-emergence herbicide (Grossbard & Atkinson, 1985). Since then, its application has grown quickly, making it the most popular and effective herbicide in the world today (Baylis, 2000; Duke & Powles, 2008). The ability of this active ingredient to translocate throughout treated plants and control re-sprouting in perennial weeds, along with a generally favorable environmental profile that includes strong binding and inactivity in soils and rapid biological degradation in most soils, water, and sediments, are some of the factors that have led to its success and widespread adoption. (5-enolpyruvyl-shikimate-3-phosphate synthetase, or EPSPS) is an enzyme of the shikimic acid pathway of plants. Its mode of action is peculiar to plants. (iii) Additionally, it has a minor ecological impact in forest environments (Durkin, 2003; Durkin, 2011) and is naturally low toxicity to animals (Giesy *et al.*, 2000; Duke & Powles, 2008: Arshad *et al.*, 2021) Data on the multi-sectoral applications of glyphosate-based herbicides gathered over forty years of laboratory and field research indicate that this is possibly the most thoroughly researched herbicide ever.

Up until recently, it was generally believed that the biggest threat to the continued widespread use of glyphosate was the emergence of weeds resistant to the herbicide due to intensive use in genetically modified agricultural cropping settings. This issue brought to light the necessity of more creativity and variety in weed control techniques, especially in the agriculture industry where most applications take place (Duke & Powles, 2008; Powles, 2008). The public concerns about glyphosate use and human health have, however, increased and come back into prominence as a result of the substance's recent designation as a probable human carcinogen (International Agency for Research on Cancer, 2015). The increased focus on glyphosate has also brought to light broader social issues related to its use, such as the growing dependence on genetically modified crops (Friends of the Earth Europe, 2013), corporate dominance over the cultivation and manufacturing of food and fibre (GREENPEACE, 2016), the wider application of pesticides, or general worries about the over-exploitation of natural assets (Conservation Council of New Brunswick, 2017).

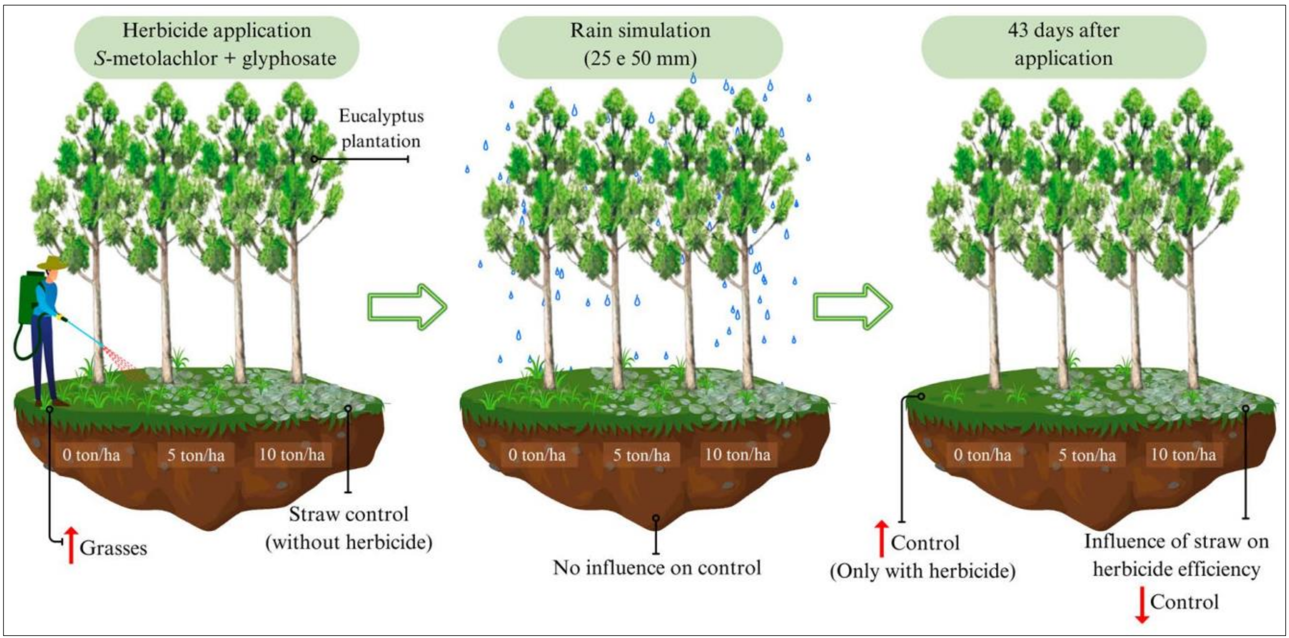

Figure 5: Efficacy of S-metolachlor + glyphosate for Weed Control in Forests (Duque *et al*., 2023)

Glyphosate-Based Herbicide Use in Planted Forest Management Internationally

It has been demonstrated that competing vegetation has detrimental short and long-term effects on the output of timber worldwide (Wagner *et al.*, 2006). As a result, with the creation of integrated competitor control measures, vegetation management is seen as a crucial silvicultural practice. Herbicides are one of many tools available to foresters in global forest vegetation management programs to improve planting success and regeneration, enabling the sustainable use of the natural resource that yields a vast array of wood products. Forest shareholders are responsible for ensuring environmentally conscious and sustainable management of this resource because humans use forest resources and derivative products widely around the world to meet basic needs like fuel, building materials for homes, and writing materials, among many other needs (Ellison *et al.*, 2017).

Herbicide treatments are normally carried out in the establishment phase of forest cultivation programs, which is defined as the first two to three years of a cycle or until canopy closure takes place (Wagner *et al.*, 2006). The special features of the context of usage in terms of temporal and spatial scale, receiving atmosphere, degree of regulation, and general oversight, must be taken into consideration when evaluating the risks related to herbicide use in planted forest management. For instance, glyphosate-based herbicides are usually applied several times to the same area of planted forest over a duration of rotation that varies from approximately 8 years (e.g., Eucalyptus plantations in South Africa) to more than 50 years (e.g., Picea plantations in Canada), in contrast to the repeated applications to the similar area year over year in many agricultural farming scenarios. In certain nations, each year just a small percentage of the total base of wooded land is genuinely harvested, planted, and managed. Herbicide use on industrial forest land was reported by survey participants in 2011 to have affected 4.4% of the USA's total managed area. According to the USA region, the respondents treated 0.26%, 2.6%, and 5.6% of the total managed area in the North, Pacific Northwest, and South, respectively, with herbicides (Herbicide Use Patterns, 2011; National Forestry Database, 2015).

Herbicides founded on glyphosate are the preeminent agents utilized globally for vegetation regulation within cultivated forestry settings. There exists a scarcity of globally disseminated, scholarly syntheses that specifically address glyphosate utilization in these managed forests. This text presents a global synopsis concerning the prevalent application of glyphosate-formulated herbicides in cultivated forests, along with an assessment of the concomitant risks. The employment of glyphosate in these environments is intermittent and is executed at concentrations not surpassing 4 kg ha−1, adhering to legal stipulations for usage and administered by personnel with appropriate training. The most substantial likelihood of glyphosate exposure to humans occurs during the manual application phase; however, adherence to regulatory guidelines ensures that the exposure level does not breach established thresholds of toxicity. An examination of scholarly literature concerning the direct and collateral risks associated with operationally applied glyphosate herbicides reveals an absence of marked detrimental impacts on both terrestrial and aquatic wildlife. Despite the necessity for further inquiry in certain domains, such as glyphosate application in forested regions beyond the North American continent and the potential lingering effects of glyphosate residues in sediment, a majority of the critical inquiries have been satisfactorily explored through scientific research. Drawing from the broad spectrum of scientific data available, it is deduced that the use of glyphosate-centric herbicides within the framework of cultivated forest management is unlikely to invoke substantial risks to human health or to terrestrial and aquatic ecosystems (Rolando *et al*., 2017).

Risk of Glyphosate-Based Herbicides to the Forest Environment

Due of their thin, porous skin, amphibians may be vulnerable to glyphosate exposure (Durkin, 2011). In Thompson *et al*.,'s study (Thompson *et al*., 2004), the scientists calculated an upper 99th centile glyphosate value of 0.55 ppm (550 µg L−1) based on chemical evaluations of wetlands in Ontario, Canada that had been directly sprayed. The results of coincident biomonitoring on two species of delicate amphibian larvae housed in the several wetlands under investigation revealed no appreciable harmful effects. Furthermore, even at the highest allowable label rates, in situ enclosing field studies conducted in small wetland areas in New Brunswick, Canada, or ponds in northern Ontario, Canada, revealed no discernible effects on amphibian that belongs survival, growth, or development upon exposure directly to formulated glyphosate-based herbicides (Edge *et al.,* 2012; Wojtaszek *et al.,* 2004; Edge *et al*., 2011; Edge *et al.*, 2013). Similar findings were found in a field study conducted in Oregon, USA, in which the effects of clear-cutting and clear-cutting followed by glyphosate application were evaluated. The study found that for six species of frogs, there were no herbicide-related side effects (Cole *et al*., 1997).

The majority of herbicidal formulations containing glyphosate are not sanctioned for employment within aquatic milieus; nonetheless, discernible levels of both the principal active component and its associated surfactants have been ascertained in surface water bodies. These findings indicate a potentiality for these compounds to induce physiological modifications in aquatic life forms. The degree of acute toxicity exhibits considerable variability among species across different taxonomic groups, with the level of toxicity contingent upon the specifics of the exposure, encompassing its timing, intensity, and vector. Recent scholarly investigations into the impact of glyphosate on amphibian species have highlighted a heightened susceptibility relative to other vertebrates. This increased sensitivity has been attributed to the unique life history characteristics of amphibians and their dependence on both aquatic and terrestrial habitats for their lifecycle (Annett *et al.,* 2014).

An investigation was conducted applying a series of glyphosate concentrations (525, 1050, 2100, 4200, and 8400 g active ingredient per hectare; with the recommended field application rate (RFAR) being 2100 g active ingredient per hectare) to seedlings aged four weeks in a controlled greenhouse setting. The parameters assessed included phytotoxicity, inhibition of growth, and herbicide susceptibility. The chosen gradient encompasses glyphosate doses typically utilized in agricultural settings, as well as higher concentrations that could inadvertently affect forest remnants through drift or excessive application. The experimental protocol adhered to established guidelines concerning vegetative vigor, specifically those addressing post-germination herbicide treatment. Observable lethal or sublethal responses were recorded across all plant species post-application, with a quarter of the RFAR resulting in severe phytotoxic effects or mortality in half of the species, and growth retardation in 70% of them. The outcomes demonstrate a spectrum of glyphosate sensitivity among the tested species; some exhibited extreme vulnerability, perishing at just 25% of the RFAR, while others were categorized as herbicide-resistant. Therefore, it is evident that forest remnants' flora may experience significant adverse impacts due to glyphosate usage in adjacent agricultural lands. The lethal and sublethal consequences of glyphosate on non-target vegetation could lead to a decrease in biodiversity within native forests embedded in agricultural landscapes and potentially contribute to the emergence of herbicide-resistant weed biotypes, given their repeated exposure to low glyphosate levels (Florencia *et al.,* 2017).

Regulatory Framework

In the US, farmworkers are a demographic at risk for severe illnesses and injuries related to the environment and their jobs, as well as health inequalities commonly linked to poverty. One of the main causes of illnesses and injuries sustained by farmworkers at work is pesticides. The effectiveness of farmworkers' safety training initiatives has not been thoroughly assessed. This investigation, which is based on the Health Belief Model, looks at how safety information influences farmworkers' perceptions of pesticide safety risk and control, as well as how those perceptions impact their knowledge and safety practices. The Preventing Agricultural Chemical Exposure in North Carolina Farmworkers' Project, which involved 293 agricultural laborers in eastern North Carolina, provided the basis for the data interviews that were done in 1999. Items from interviews were used to create measures measuring perceived pesticide risk and perceived pesticide control. Farmworkers reported relatively high levels of perceived danger from pesticides and perceived control over pesticide safety, according to an analysis of the items and scales. Learning about the safety of pesticides (such as warning signs) decreased perceived risk and raised perceived control. Perceived danger was substantially correlated with awareness of pesticide exposure. Perceived risk, however, was unrelated to safety behavior and only weakly correlated with safety knowledge. Knowledge of pesticide exposure was not correlated with perceived control, although safety behavior and knowledge were. Communities' sovereignty over their environment is a fundamental component of environmental justice. These findings suggest that in order to effectively implement occupational pesticide safety, pesticide management education needs to address issues of farmworker control (Arcury *et al.*, 2002).

Sustainable Practices

There is increasing evidence that biodiversity supports ecosystem functioning (Cardinale *et al.*, 2012), and there is general agreement that loss of biodiversity lowers the efficiency with which ecosystems recycle nutrients, create biomass, and accumulate carbon (Felipe-Lucia *et al.*, 2020). Intense land uses that seek to maximize a particular service may also cause a loss in specific ecosystem services since management has the power to directly or indirectly modify biodiversity and ecological functions. Therefore, there may be trade-offs between management goals that priorities generating a specific set of ecosystem services and a wide range of other ecosystem services (Felipe-Lucia *et al.*, 2020; Martin-Lopez *et al*., 2014). We looked at research that has been done on herbicide treatments' effects on the main biotic components of northern wooded ecosystems, mostly after 1990. All other biotic components alter as a result of changes in the vegetation. It is typical for non-conifer vegetation to be reduced over a period of two to five years after applying broad herbicide applications. However, fungal components appear to be mostly unaffected. Longer-term changes correspond to conifer stocking, site quality, and the capacity of conifers to dominate treated sites. Short-term vegetation losses in cover, density, or associated biomass, if they develop, are specific to species and/or forest groups. Treatments with herbicides neither decrease nor increase the species richness of plants at the stand and landscape levels. When foresters utilize those methods for managing boreal or boreal mixed wood, they rarely result in monocultures. The overall welfare (survival, growth, and reproduction) of animals in treated regions is not directly impacted by the active chemicals in herbicide products used in forestry in northern habitats. It is necessary to assess specific stand-level forest management activities in light of the landscape mosaic and the intended future forest conditions. This includes examining the effects of site preparation and conifer release. Since European settlers started taking wood from the boreal and boreal mixed wood habitats, hardwoods have steadily supplanted conifers on a large scale. Herbicides offer a secure and efficient means of reestablishing conifers in ecosystems that were formerly dominated by them. As of right now, forest scientists can reasonably infer how different herbicide treatments affect the growth of conifers and other environmental factors. But in terms of treatments (replicas, drugs, combinations, or time) that might be employed in the future, they must constantly update their knowledge (Lautenschlager *et al.*, 2002).

Alternatives to Herbicides

Herbicide-based weed competition management offers a significant chance to boost forest yields and reduce expenses for production. However, if not used properly, many herbicides harm crop trees. Suboptimal weed control is therefore frequently tolerated in modern silvicultural practices. Three strategies can be used to achieve herbicide selectivity for weeds relative to crops: avoidance, tolerance, and persistence. In tree plantations, avoidance and species-level tolerance are currently the only ways to achieve broad spectrum herbicide selectivity. The ability to confer herbicide tolerance and resistance to particular tree genotypes is made possible by the emerging biotechnologies, which opens up significant possibilities for improving weed control. Large-scale plantations of angiosperms trees-hardwoods resistant to herbicides would be possible in industrialized nations. Understanding an herbicide's main mechanism of action is essential to assessing its potential for use in a biotechnology program as well as its stress-related impacts on the forest stand. Herbicide detoxifying (metabolism), overproduction of the herbicide's targets enzyme, and modification of the herbicide's target protein are a few of the most promising strategies for establishing herbicide tolerance or resistance in forest trees. Soma clonal selection and recombinant DNA technology may be able to introduce genes for these traits into trees. Glyphosate, sulfonylureas, and imidazolinones are good candidates for herbicides to which forest trees may acquire resistance based on a number of scientific, commercial, and environmental factors (Nelson *et al.*, 1986).

While mechanical operations are more likely to preserve non-crop tree flora than herbicide treatments when applied widely (Wagner *et al*., 2006), their large-scale adoption in the Pacific Northwest is sometimes limited by their related costs and the difficulty of implementing such treatments in difficult terrain. As these stands recover following early herbicide treatments, they seem to play a significant role as foraging area for ungulates, songbirds, and some pollinators within managed forested landscapes, even though herbicide-induced losses in plant variety in harvested stands occur. Fostering vital habitat components for these species such as preserving native herbaceous and broadleaf vegetation may result in the transfer of services supplied by wildlife to nearby woods and farmlands (Krimmer *et al*., 2019).

Future Outlook

Ecosystem services, which are the benefits that humans receive from nature in terms of supplying, regulating, supporting, and cultural aspects, have been increasingly important in environmental policies and management during the past few decades (Costanza *et al.*, 2017). While the provision of services like food and fibre supports economic systems, the other possible benefits that humans may receive from biodiversity and ecological processes are less clearly quantified, particularly in relation to the extent to which they are impacted by the production of commodities (Bennett *et al.*, 2009). Indeed, due to worries about potential negative effects on the provision of products to society, many characteristics of biodiversity and natural variability (such as competing vegetation, herbivorous creature's disease, and natural events) may be viewed as environmental disservices in production systems (Ceausu *et al.*, 2019). In order to support a consistent output of crop species that are economically useful, intensive land management techniques frequently seek to reduce natural variability (Wagner *et al.*, 2006).

The production of timber is an economically measurable ecosystem function, and it is anticipated that more forestland will be under high-production intensive forest management as the world's demand for wood products rises (Food & Agriculture Organization of the United Nations, 2018). While making up just around 7% of the world's forestland, forest plantations supply almost 33% of the amount of legally acquired round wood that is sold on international markets (Barua *et al*., 2014; Brockerhoff *et al*., 2013). Even-aged forest management, achieved by the use of clear-cut harvest activities, vegetation management (e.g., herbicides), and thick monospecific tree plantings, is a common feature of intensively managed plantations in temperate regions. By regulating early-successional floristic circumstances that might otherwise obstruct crop-tree growth and development, these methods promote the production of high-value wood species (Wagner *et al.*, 2006).

Adjusting herbicide medication so that they retain regions of native vegetation (e.g., spot treatments, non-sprayed strips or areas) while still suppressing enough competing vegetation to support tree growth is the best stand-level execution to reduce trade-offs between ecosystem services, ecology, and timber. (Stokely and others, 2022).

CONCLUSION

In summarizing the complexities of herbicide use in forestry, it is essential to recognize their dual role in enhancing forest productivity while also posing potential environmental risks. Herbicides, as a tool for managing competing vegetation, have significantly increased wood volume yields, proving vital for the economic sustainability of forestry. However, this comes with concerns for biodiversity conservation, ecosystem balance, and water quality. The review underscores the necessity for a balanced approach that considers the long-term ecological impacts, advocates for responsible use, and explores alternative management strategies. The evolving landscape of forest management now calls for innovative practices that support both production goals and ecological integrity, ensuring that intensive land management aligns with environmental stewardship and public health.

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