

# Mowing matters: examining the role of current mowing practices in the spread of *Lupinus polyphyllus* along Swedish road verges

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# Abstract

Invasive alien species pose a significant threat to global biodiversity, with invasive alien plants (IAPs) like *Lupinus polyphyllus* causing widespread ecological disruption. Road verges play an important role in facilitating the spread of IAPs by acting as dispersal corridors and providing disturbed habitats that favor their establishment. *L. polyphyllus*, with its highly invasive characteristics, has gathered a raising concern in Sweden, where it outcompetes native flora and disrupt existing ecosystems. In this study I investigate the spread of *L. polyphyllus* along Swedish road verges, with a focus on how road verge maintenance and adjacent land use influence lupine dispersal and expansion.

The study area encompassed parts of Heby and Sala municipalities, where Trafikverket has conducted lupine inventories since 2021. During summer 2024, I participated in these inventories as part of my employment at Trafikverket, mapping lupine occurrences using car and GPS-based methods. Data over the three year period (2021-2024) was analyzed to measure lupine stand expansion (change in length of lupine stands established in 2021) and the establishments of new lupine individuals (individuals noticed 2024, outside of pre-existing stands). Information regarding mowing dates and frequencies was obtained from PEAB Heby. The results indicated a significant expansion of lupine stands, with an average increase of 8.41 meters per stand. They also revealed great dispersal through the establishment of 264 new lupine individuals. Double mowing was found to reduce the rate of establishment of new lupine individuals compared to single mowing, but it did not limit the expansion of already established stands. The gathered mowing regimes were not aligned with the recommendations based on lupine phenology. Most mowing events took place either at seed maturation or afterwards resulting in higher possibilities for seed dispersal through machinery. Moreover, a trend suggested that lupine stands expanded more along road verges adjacent forests, possibly due to reduced competition and soil conditions.

My results highlight a misalignment between current mowing practices and recommended strategies for controlling *L. polyphyllus*. The present situation requires new management techniques which include planned mowing before lupine seed maturation together with repeated area surveillance of newly- and non-invaded areas. Special attention should be given to the role of mowing machinery in facilitating lupine seed dispersal, and strategies on how to mitigate this issue. However, targeted approaches for IAPs control and biodiversity conservations are not always aligned. Balancing these two objectives will require site-specific approaches as well as collaboration across stakeholders. Finally, I state the urgency of actions against the spread of *L. polyphyllus*, as climate change and urbanization are expected to increase the threat of IAPs.

## Nyckelord/Keywords

*Lupinus polyphyllus*, lupine, garden lupine, road verges, infrastructure, invasive species, invasive plant species, invasive alien plant species, IAPs, dispersal, mowing, land use, landscape analysis



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# 1 Introduction

## 1.1 Invasive alien species and their global Impact

Invasive alien species are a great global concern, recognized as one of the leading threats to biodiversity (IPBES, 2023; Sage, 2020). These species are generally understood as non-native species introduced by human activities that spread aggressively and cause damage to ecosystems, economies, or human health (IUCN, 2020). The introduction and spread of invasive alien species have been enabled by human activities such as international trade, transportation, and changes in land use (Hulme, 2009; Pauchard & Alaback, 2004; Sage, 2020). Alongside climate change (Roy et al., 2024; Sage, 2020), these human influences have driven a rapid increase of IAS, with projections estimating a 36% increase in their numbers between 2005 to 2050 (Seebens et al., 2021).

Among invasive alien species, invasive alien plants (IAPs) have the ability to outcompete native vegetation, alter habitats, and disrupt ecosystem functions (Zim Dahl & Brown, 2018). The spread of invasive alien plants is a multi-phase process that starts with their introduction to a new environment, followed by successful establishment and expansion (growth of smaller plant populations) (With, 2002). Dispersal, defined as the successful movement of plant propagules away from parent plant (Cousens et al., 2008), allows IAPs to reach to new sites, leading to the formation of spatially distributed populations (With, 2002). One of the worst IAPs in Europe and North America, for example, is the Japanese knotweed (*Fallopia japonica*) (Fennell et al., 2018; Nentwig et al., 2018). It spreads aggressively along riverbanks and infrastructure, where it displaces native flora, disturbs wildlife movement and increases the risks of flooding and erosion (Fennell et al., 2018; Shaw, 2013). In Africa, IAPs are widely established because of insufficient control over species introductions (Makoni, 2020). The Fabaceae family's Wattle species (*Acacia sp*) is one of these IAPs. This species can alter ecosystems in a variety of ways, including reducing biodiversity, raising the risk of wildfires, and causing water scarcity (Le Maitre et al., 2011).

Northern countries have historically faced fewer challenges with IAPs due to their glacial history and young flora (Agrell, 1979; Bevinger, 2021). Human activity has had a significant impact on the post-glacial recolonization of flora, making it difficult to distinguish between natural colonization and IAPs (Tyler et al., 2015). Additionally, this young post-glacial flora consisted of species with highly competitive and dispersal abilities, evolved under harsh climatic conditions and nutrient-poor soils, reducing niche availability for IAPs (Bevinger, 2021; Tyler et al., 2015). However, the focus on IAPs has during recent years increased as climate change and globalization accelerates their establishment and spread (Sage, 2020; Tyler et al., 2015). More than 50,000 plant IAPs been documented in Sweden via Artportalen over the last decade (Artdatabanken, n.d.).

## 1.2 *Lupinus polyphyllus*: characteristics and invasiveness

The perennial herb *Lupinus polyphyllus*, also known as garden lupine or simply lupine, is a member of the Fabaceae family (Mossberg et al., 2018; Wissman, 2015). While it is not yet listed as an IAPs of Union concern (EU, 2022), it is widely acknowledged as one of the most troublesome IAPs in Europe (Bevanger, 2021; Eckstein et al., 2023; Nentwig et al., 2018; Tyler et al., 2015). The invasiveness of lupines is attributed to their growth habits, which enable them to spread easily and thrive in diverse environmental conditions. They frequently outcompete native plant species, thereby reducing species richness (Dániel-Ferreira et al., 2024; Fremstad, 2010; Sober & Ramula, 2013).

Originally native to North America (Fremstad, 2010), *L. polyphyllus* was first introduced to Sweden in the 1870s (Hylander, 1972). It was initially cultivated as a garden plant and used to improve the quality of degraded soils (Fremstad, 2010; Hiltbrunner et al., 2014; Tyler et al., 2015). Over time, lupines escaped garden cultivation and is now considered one of the most problematic IAPs in Sweden (Naturvårdsverket, n.d.-b). Despite being so invasive, lupines are not nationally regulated as an IAPs, but it is under consideration for inclusion on the regulatory list (Naturvårdsverket, 2022). *L. polyphyllus* is still a common garden plant because of its eye-catching characteristics, which has helped it spread (Wissman, 2015).

Characteristically, *L. polyphyllus* can grow over a meter in height, and produces elongated, vibrant inflorescences in racemes (Eckstein et al., 2023; Fremstad, 2010). Lupines are strong competitors for light due to their size and bushy growth (Thiele et al., 2010; Valtonen et al., 2006). Their deep taproot system is sparsely branched and thickens with age and is frequently developing root- nodules (Chmelíková & Hejman, 2012). Within these nodules, symbiotic cyanobacteria enable nitrogen-fixation, altering soil composition and reducing suitability for many already established plant species (Hiltbrunner et al., 2014).

The plant's prolific reproductive capacity contributes to its invasiveness. Lupines can reproduce vegetatively through clonal root shoots, but sexual reproduction via seed dispersal is the most common form of reproduction (Fremstad, 2010; Ramula, 2014). Each inflorescence can on average yield 47 pods containing 4 to 12 seeds each (Eckstein et al., 2023; Wissman, 2015). A single plant can generate up to ca 2500 seeds annually (Aniszewski, 2001; Naturvårdsverket, 2022). These seeds can remain viable in the seed bank for up to 50 years (Fremstad, 2010). Moreover, even after shoot damage the plants can regrow (Ramula, 2020). Depending on latitude (Ludewig et al., 2022), *L. polyphyllus* begins flowering from May- June until late August- September (Eckstein et al., 2023; Fremstad, 2010), with seed- maturing generally occurring from mid-June to the end of July (Klinger et al., 2020; Ludewig et al., 2022).

## 1.3 Role of infrastructure in the spread of invasive plants

Infrastructure habitats, such as road verges and railways, facilitate the spread of IAPs by acting as pathways for seed dispersal and population expansion (Christen &

Matlack, 2009; Hulme, 2009). By increasing connectivity between habitats in fragmented landscapes, this enables IAPs to establish in new areas through both natural dispersion methods (e.g., wind, wildlife) and human-assisted vectors like vehicles and machinery (Auffret et al., 2014; Lázaro-Lobo & Ervin, 2019; Lippe et al., 2013). The constant anthropogenic disturbances occurring by infrastructural elements, including construction work (soil disruption, habitat fragmentation), road verge management (e.g. mowing), and pollution (salts, heavy metals) create unstable, nutrient-poor conditions that favor stress-tolerant IAPs over native species (Tschan, 2018; Lázaro-Lobo & Ervin, 2019). As global infrastructure development accelerates, the spread of IAPs is expected to increase significantly (Lázaro-Lobo & Ervin, 2019; Pauchard & Alaback, 2004).

Among these infrastructure habitats, road verges can be species-rich by functioning as small, remnant habitats resembling semi-natural grasslands historically shaped and maintained by human activities (Auestad & Rydgren, 2011; Auffret & Lindgren, 2020; Cousins & Eriksson, 2002; Dániel-Ferreira et al., 2023). Road verges serve as landscape corridors which enable native species along with IAPs to spread across fragmented landscapes (Lázaro-Lobo & Ervin, 2019). These corridors support native biodiversity, yet they permit IAPs spread into new areas (Lázaro-Lobo & Ervin, 2019). Although road verges often share features with semi-natural grasslands, such as open vegetation, dry conditions, and nutrient-poor soils (Cousins, 2009; Cousins & Eriksson, 2002), they are different when it comes to anthropogenic disturbances. For example, the soil is often composed of excavation material that differs in composition from adjacent soils (Vägverket, 2007). This excavation material is frequently contaminated with a seed bank containing IAPs, which further contributes to the spread of these species (Tschan, 2018; Wissman, 2015).

#### 1.4 Current control strategies for garden lupine

*L. polyphyllus* has been shown to negatively affect species richness along Swedish road verges (Dániel-Ferreira et al., 2024), thus making its control an important management concern (Lennartsson et al., 2021). However, control measures for lupines along road verges vary in effectiveness, feasibility, and available knowledge. Certain methods, such as pesticides and the use of biological control, are either too risky or untested for widespread use (Fremstad, 2010; Trafikverket, 2024a). Other methods, such as grazing, excavation (removal of soil and root systems) and root pulling, have produced positive results (Black et al., 2014; Wissman, 2015), but are frequently considered too expensive for large-scale implementation (Wissman, 2015).

Mowing is the most used method for controlling garden lupines in Sweden as it is cost effective, though there is limited information on how to optimize its effectiveness in different ecological contexts (Wissman, 2015). In traditional haymaking mowing is combined with biomass removal, which helps suppress tall, competitive species and makes short-lived vascular plants more prevalent (Lennartsson & Westin, 2019). Through common garden experiments, Ramula (2020) demonstrated that a single mowing event with biomass removal significantly reduced lupine plant survival. The

effects became apparent already in the following year, implying that annual mowing of road verges could help to control lupine spread (Ramula, 2020). However, the mandatory mowing of Swedish road verges is often carried out without biomass removal (Runesson, 2012; Trafikverket, 2024c; Vägverket, n.d). This could reduce the effectiveness of mowing in controlling lupine spread.

The timing and frequency of mowing is also shown to significantly influence germination percentages of IAPs (Bourdôt et al., 2016; Lommen et al., 2018; Rim et al., 2023) as well as lupines (Klinger et al., 2020). Mowing twice a year is shown to lower the survival of taller shrubs (Jantunen et al., 2007a; Parr & Way, 1988). For lupine control, Naturvårdsverket (2022) recommends mowing 2–3 times a year. This frequency could reduce lupines capability of resprouting as well as limiting seed production (Fremstad, 2010; Naturvårdsverket, 2022). Additionally, cutting lupines before seed maturation is crucial, as mature seeds have the highest germination rates, better seed bank persistence, and reduced susceptibility to mold infections (Brobäck, 2015; Klinger et al., 2020). According to recent Swedish research from Blomqvist et al (2025), mowing is the most efficient when the lupines root reserves are at their lowest and the concentration of nutrients in the shoots is at its highest. This timing ensures that cutting occurs before seed maturation and dispersal (Blomqvist et al., 2025).

Swedish mowing practices for state roads are regulated by the Swedish Transport Administration (Trafikverket, 2024b) and it usually involves two annual cuts. The first cut targets a narrow strip close to the road edge. Later, a second cut covers the remaining area up to approximately 10 meters from the road edge. These mowing practices take place from June to late August or September. (Trafikverket, 2024c). A recurring issue in Swedish reports on IAPs in infrastructure is the role of maintenance work, particularly how mowing machinery contributes to the dispersal of IAPs seed (Tschan, 2018; Wissman, 2015).

Since 2015, the EU regulation on invasive alien species (EU, 2022) requires Trafikverket to implement measures to limit the spread of IAPs. Trafikverket has several projects to manage lupines along Swedish road verges (Trafikverket, 2024). Furthermore, Trafikverket collaborates with universities to create new solutions for managing IAPs along traffic infrastructure (Faith-Ell, 2023). One of these collaborations is TRIIAS, a research initiative that focuses on IAPs in infrastructure environments (TRIEKOL, n.d.). However, Trafikverket still lack a framework with management guidelines for *L. polyphyllus* (Litborn, 2024).

## 1.5 Thesis aim and research questions

The spread of IAPs like *L. polyphyllus* often follows a nucleation pattern (Moody & Mack, 1988); Established stands act as sources of propagules (seeds) that disperse to create smaller populations. These small populations can expand and merge with adjacent populations. Through a combination of dispersal and expansion, this accelerates IAPs spread (Moody & Mack, 1988). Thus, high lupine cover on road verges may increase the establishment of new individual lupines nearby due to higher propagule pressure.

It is considered that effective management of *L. polyphyllus* should prioritize the control of areas newly inhabited by lupines, as larger established lupine populations are much harder to manage (Helldin et al., 2022). Early detection of newly established populations provides quicker and more cost-effective methods by reducing the risk of larger populations (Simberloff et al., 2013). Moreover, early intervention can prevent lupines from establishing in sensitive and biodiverse environments, thus contributing to biodiversity preservation (Simberloff et al., 2013; Wissman, 2015). Despite the importance of early detection, knowledge about where to what extent lupines spread is still limited (Lennartsson et al., 2021; Tschan, 2018; Wissman, 2015).

Landscape-scale studies are crucial for studying IAPs to combat further establishment of the species. Smaller scale studies often lack applicability to the broader and more widespread contexts in which these species occur (Kettenring & Adams, 2011; Stohlgren et al., 2001; With, 2002). Given the wide distribution of lupines, there is a need for research that considers these species on a larger, landscape scale. Moreover, even though Trafikverket follows a method for road verge maintenance, it is unclear whether this method is specifically tested for its impact on species such as *L. polyphyllus* or how consistently it is applied in practice.

To address the above knowledge gaps, this study aims to explore how road verge management and adjacent land use influence the spread of *L. polyphyllus* along Swedish road verges. To track potential lupine expansion, I will analyze changes in the length of established lupine stands over a three-year period (small lupine populations present at the start). Further, to explore dispersal patterns and the rate of new establishments, I will analyze the establishment rate of individual lupines (new plants outside of pre-existing stands established by the end of the three-year period). Specifically, I ask:

- 1) Does the length of lupine stands change over time? If so, how?
- 2) How do current mowing practices relate to the phenological stages of lupines (*Lupinus polyphyllus*)?
- 3) How do road verge management practices and adjacent land cover types influence the expansion of established lupine stands along road verges?
- 4) What effect do land use type, frequency of mowing, and the proportion of road verge already covered by lupines have on the rate at which lupine individuals establish themselves along road verges?
- 5) How do the proportion of road verges covered by lupine, mowing frequency, and land use type affect the rate of establishment of lupine individuals along road verges?
- 6) Does surrounding vegetation height and/or density affect the rate of establishment of lupine individuals?

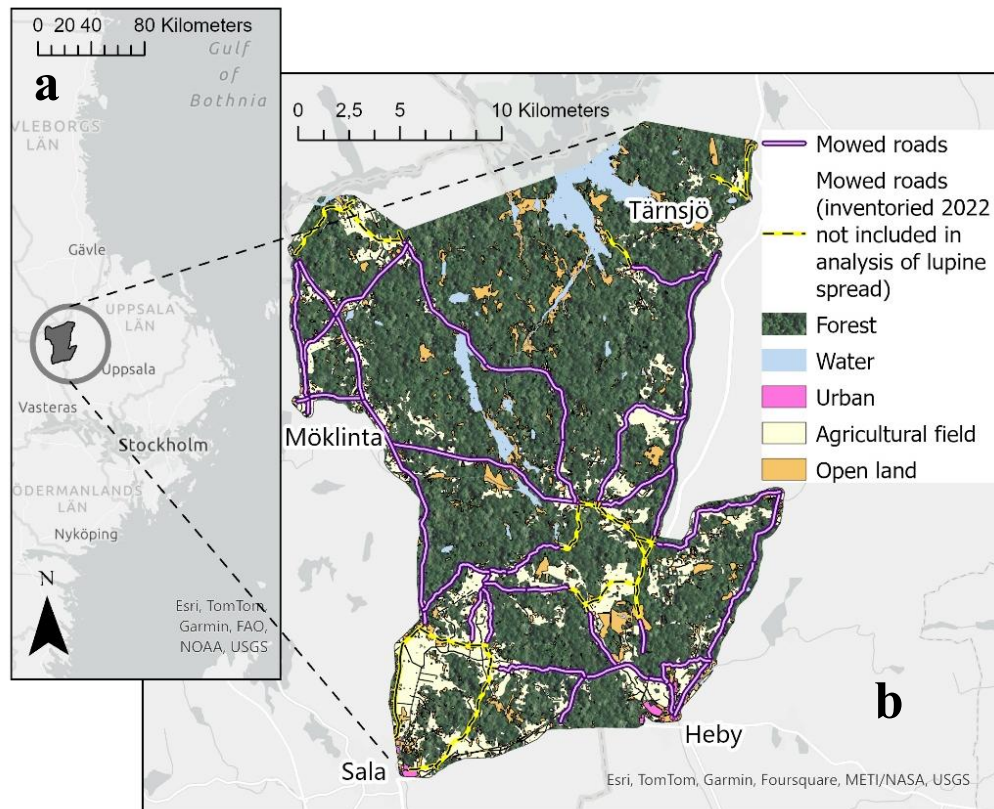
## 2 Method

### 2.1 Study area

The study area (Figure 1) is situated within Sala and Heby municipalities, located in the eastern central part of Sweden. It is a part of the Swedish Boreo-nemoral zone, just south of the ecological boundary known as Limes Norrlandicus (Ahti et al., 1968; Diekmann, 1994). This transitional zone is characterized by a mix of coniferous and deciduous trees, creating species-rich forest communities (Diekmann, 1994).

The municipalities' northern regions are dominated by relatively flat terrain, located south of the Dalälven river system. In contrast, the south-eastern part has a more varied landscape, with open areas and several valleys formed by bedrock made of granite with limestone streaks (Diekmann, 1994; NE, n.d.-a, n.d.-b). Moraine are the most common soils, followed by fine sand, glaciofluvial sediments, clay, and peat (SGU, n.d.). However, road verges often deviate from this soil composition due to anthropogenic construction practices, such as the use of excavation materials during road development (Vägverket, 2007; Wissman, 2015). The common land use of Heby and Sala municipality is predominantly forested, with mainly coniferous forest covering 68 % of the area. Agricultural land accounts for 20%, and urbanized areas make up only 3.9% (SCB, n.d.). Wetlands and fens are common, particularly in areas adjacent to lakes and rivers (NE, n.d.-a, n.d.-b). The region experiences a continental-influenced climate, with cold winters averaging  $-3^{\circ}\text{C}$  and summers averaging  $17^{\circ}\text{C}$ . Annual precipitation ranges from 400 to 450 mm, with frequent snowfall and snowstorms during winter (SMHI, 2023).

Heby and Sala municipalities consists of a network of state, municipal, and private roads. Municipal roads are maintained by the municipalities, state roads by Trafikverket (delegated to PEAB Heby), and private roads by local road associations. (Naturvårdsverket, n.d.-a; Nord, 2024a).



**Figure 1.** Study area. a) Location of the study area in Sweden (upper left). b) Map of the study area. Roads marked with red represent mowed road verges included in the analysis, with mowing dates collected in 2023. Dashed lines represent mowed road verges not included in the analysis. Land use categories obtained from Lantmäteriet GSD-Topographic Map.

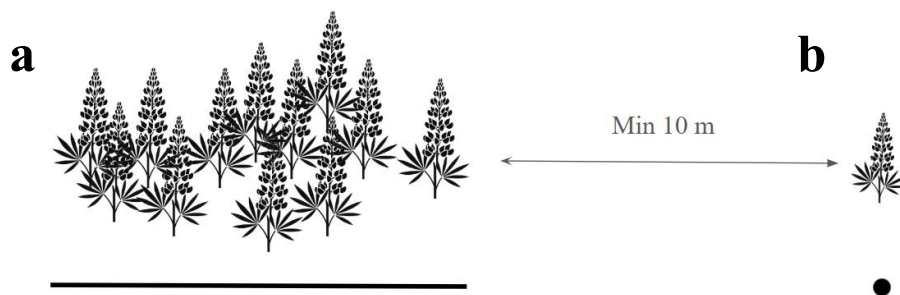
## 2.2 Field work

As part of the TRIAS research program, the Swedish Biodiversity Centre (Centrum för biologisk mångfald) at the Swedish University of Agricultural Sciences, SLU has conducted lupine inventories across several regions in Sweden since 2021 (Helldin et al., 2024). The study area in Sala/Heby municipality was inventoried in 2021 and expanded in 2022 to include additional roads. As a part of my employment at Trafikverket 2024, my colleague and I repeated the inventory during 4-27 July, following the methodology described by Helldin et al. (2024). I utilized both data previously collected from 2021, and data collected during my employment 2024 to analyze the spread of lupines along road verges for this thesis. Due to methodological inconsistencies in the 2022 lupine inventory compared to the 2021 and 2024 inventories, the data from 2022 was excluded from the analysis of lupine spread.

The survey was conducted by car to maximize time efficiency, requiring a two-person team: one driver and one observer. The observer recorded lupine occurrences using an iPad with the ESRI Field Map application, achieving GPS accuracy of 5-10 m. The speed of the vehicle while performing the survey ranged from 20–50 km/h, but high-speed roads (>80 km/h) were excluded for safety and data reliability.

### *Lupine stand mapping*

Lupine stands were mapped on a basemap as polyline features (Figure 2a), with GPS coordinates recorded at the start and end of each stand, which gives the stand a measurement of length in meters. The vehicle was stopped at these points to mark the boundaries of the lupine stands. Existing line features (established lupine stands) from previous inventories were updated to reflect changes in stand length. New occurrences within 10 meters of existing stands were incorporated into the original features, while those beyond 10 meters were mapped as new occurrences (new lupine stands or individual lupines).



**Figure 2.** Mapping of lupine presence in field. The distinction between lupine stands and/or individual plants was based on a 10-meter distance threshold. a) Lupine stand mapping: a lupine stand (small, localized lupine populations) was marked as a polyline feature, with GPS coordinates collected at its start and end points. b) Individual lupine plant mapping: Individual lupine was mapped as a point feature, using a single GPS coordinate. These individual lupines were all established after the initial surveys in 2021/2022.

### *Individual lupine plant mapping*

A methodological addition after the 2021 and 2022 inventories was the inclusion of point features, used exclusively to map individual lupine plants located more than 10 meters from existing stands (Figure 2b). These point features represent lupines that emerged after the initial surveys, providing a clear distinction from the previously documented occurrences. When a lupine individual was found, the vehicle stopped beside it, and GPS coordinates were recorded to locate its position. For each individual lupine plant recorded as a point feature, the surrounding vegetation's height and density were classified into predefined categories (Table 1).

**Table 1.** Vegetation height and density classifications recorded for individual lupine plants mapped as point features. Vegetation height was categorized based on the height of the vegetation surrounding the lupine plant at the time of the survey, while vegetation density was assessed based on how much of the ground was covered by vegetation near the lupine individual.

<b>Vegetation height</b>	Definition	<b>Vegetation Density</b>	Definition
<b>Veg low</b>	Vegetation < 10 cm	<b>Veg sparse</b>	Predominantly bare soil
<b>Veg moderate</b>	Vegetation 10- 30 cm	<b>Veg medium</b>	Soil mostly cleared of vegetation
<b>Veg high</b>	Vegetation < 30 cm	<b>Veg dense</b>	Ground completely covered by vegetation

## 2.3 GIS analysis

### *Road and management data*

Road data were obtained from Trafikverket's Nationella vägdatabas (Trafikverket, 2025). On the 8<sup>th</sup> and 16<sup>th</sup> of October, I visited PEAB in Heby to collect mowing times and coordinates from their database. I added this information to all the state roads within the study area that had documented mowing times. For the purpose of gathering road management data, all roads within the study area were included, regardless of the inventory year (2021, 2022, or 2024) (Figure 1).

### *Land cover data*

Land cover data were obtained from Lantmäteriet's GSD-Topographic Map (Lantmäteriet, 2021) and subsequently reclassified into four categories: Urban, Agricultural Land, Open Land, and Forest. The categories were expected to influence lupine stand length and/or lupine individuals' rate of establishment for several reasons based on the different traits comprising each land cover type. These differences include variations in light availability, the frequency of lupine escapes from gardens, and differences in the intensity and type of disturbances (e.g. vehicular traffic, construction and road maintenance, soil disruption from agricultural machines).

The land cover within a 15-meter buffer beside the road was classified based on the land cover type with the largest proportional area in the buffer. This buffer size was selected because Trafikverket typically mows road verges up to 10 meters (Trafikverket, 2024c), and the additional 5 meters ensured the inclusion of the adjacent land use.

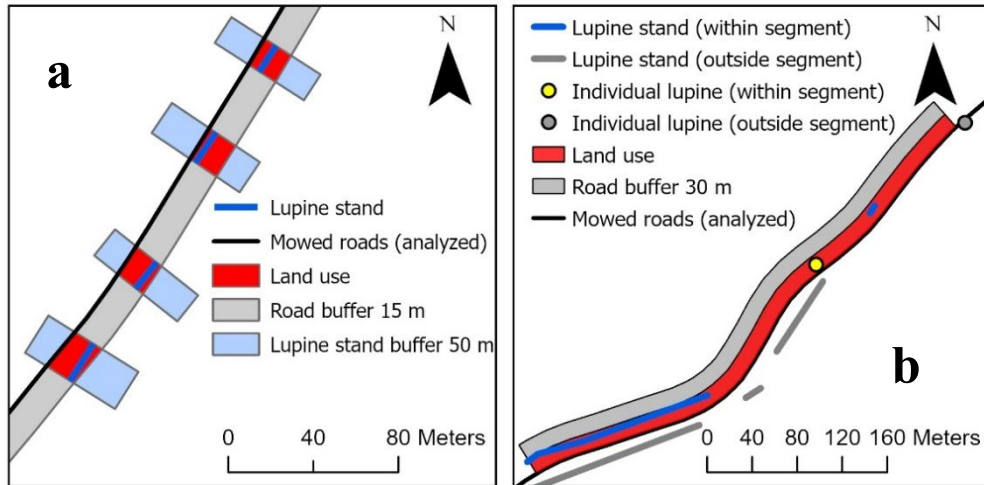
### *Analysis of lupine stands*

Established lupine stands from the 2021 dataset were manually matched to their 2024 counterparts using a shared unique ID. This allowed direct comparison of the established lupine stands between years, even if their length or position had been edited. The length of the established lupine stands for both 2024 and 2021 were calculated using the ArcGIS field calculator. Discrepancies between mapped lupine polylines and their true geographic locations compromised the accuracy of adjacent land cover type for each lupine stand. These discrepancies arose due to variability between inventory personnel, inconsistent basemap references (e.g., shifts by using different background maps) and positional inaccuracies (e.g., digitizing polylines from the road verge from inside of a vehicle). Thus, land cover type for each lupine stand were resolved through spatial processing in ArcGIS Pro (ESRI, 2023), to standardize the representation of adjacent land use.

To extract the land cover type for each established lupine stand, and to mitigate the inaccuracies described above, I analyzed the left and right sides of the roads separately. This was achieved by creating two 30-meter buffers with flat end caps on either side of the road. Lupine occurrences within the right-side buffer were assigned to spatial processing on the right side of the road, and vice versa. Any lupine occurrences falling outside these buffers were excluded to maintain spatial consistency. The following steps describe the process for one side of the road, which was then repeated for the other side:

For each lupine stand, two distinct buffers were used to obtain a single land cover type polygon (Figure 3a). First, a 15-meter buffer with flat end caps was generated along the road to capture the land cover type adjacent to the road verges. Second, a 50-meter buffer with flat end caps was constructed around each lupine line occurrence. The intersection of the 50-meter lupine buffer with the 15-meter road buffer was then extracted to define the land-use polygons associated with each lupine stand. The 50-meter buffer was chosen to ensure full coverage of the 15-meter road buffer, even if the lupine stand was located up to 30 meters away from the road. This method ensured accurate alignment of the land-use polygons with the corresponding lupine stands.

New lupine stands, identified during the 2024 inventory but absent in the 2021 inventory, encompassed by the 30 m buffers along the road where simply counted.



**Figure 3.** Spatial analysis. a) Analysis of lupine stands on the right side of the road. The red polygons represent the 15-meter buffers around the road, while the blue polygons depict 50-meter buffers surrounding each lupine stand. The intersection of these buffers defines the land-use polygons associated with each lupine stand. This figure does not include the 30-meter buffer used for assigning buffers to the right or left side of the road. b) Analysis of lupine individuals on the right side of the road. The polygons in the figure are a part of one single 500 m segment. Grey buffer represents the 30-meter road buffer for identifying lupine individual occurrences within each segment. The red polygon defines the 15-meter buffer used to determine the dominant land-use type adjacent to the road segment. Yellow dots represent lupine individuals located within the segment, while blue lines represent lupine stands within the segments. Grey features outside the 30-meter inclusion buffer are not considered in the analysis. The lupine cover in the 500 m segment was calculated as the length of the lupine stands within the segments (blue) divided by the length of each road segment (red).

#### *Analysis of individual lupine plants*

To investigate factors influencing the establishment of lupine individuals, road lines were divided into 500-meter intervals. Using the “Generate Points Along Line” and “Split Line at Point” tools, roads were thereafter divided into 500-meter segments (n=519). Two 30-meter buffers with flat end caps were created around each segment, one extending to the left and the other to the right side of the road, creating buffer polygons (30 x 500 m). The “Summarize Within” tool was used to count individual lupine- point features within these polygons. (Figure 3b)

Within each road segment buffer (30 x 500m), the lupine cover (%) was calculated as the length of all established lupine stands divided by the total road segment length (500m). To detect the dominant land use type for each road segment, each 500-meter segment was buffered by 15 meters on both sides, and the resulting polygons were intersected with the land-use vector layer. The dominant land-use type for each buffer was determined using the “Calculate Statistics” tool, identifying the land use with the largest area within each polygon.

## 2.4 Statistical analysis

### *Expansion of lupine stand length over time*

The change in the length of established lupine stands over time (measured as the distance they extend along the road verge) was assessed by calculating the difference between their lengths in 2024 and 2021. To focus specifically on pre-existing stands that were recorded during inventories 2021, those stands identified as newly established in 2024 were excluded from this analysis. A Shapiro-Wilk test indicated that the difference in length of lupine stands did not follow a normal distribution. Consequently, a Wilcoxon signed-rank test with continuity correction was performed to determine whether the change in length of the stand with time was statistically significant.

### *Road verge management practices: frequency and timing*

Road verge cutting dates were categorized into three phenological phases of the lupine: before seed maturation (weeks < 27), during seed maturation (weeks 27-30), and after seed dispersal (weeks > 30). The dates for the three phases were based on previous conducted studies (Eckstein et al., 2023; Klinger et al., 2020; Ludewig et al., 2022) and on the observations of lupine phenology within the study area performed by Dr. Juliana Dániel-Ferreira and Assoc. Prof. Tommy Lennartsson, SLU Swedish Biodiversity Centre. The phenological phases were used to determine whether the first and second mowing events occurred before or after seed maturation. The total length of road verge vegetation mowed during each phase and week was recorded in meters.

### *Effect of mowing and land cover type on established lupine stand expansion*

The effects of mowing frequency and land cover type on changes in lupine stand length were analyzed using a Linear Mixed Model (LMM) with the lme4 package in R (Bates et al., 2015). A LMM was chosen because the response variable, change in lupine stand length, is continuous and includes both positive and negative values. The model accounts for repeated measurements from the same road by including road ID as a random effect. Mowing frequency (1-2) and land cover type were used as independent variables. Lupine stands newly discovered in 2024 were excluded from the analysis to focus on pre-existing stands recorded during the 2021 inventory. Stands classified under the "urban" land cover type were excluded due to a low number of observations (n = 1). I found deviations from normality in residuals and heteroscedasticity when performing residual diagnostics using the DHARMA package in R (Hartig, 2024). In the ideal case, all parametric assumptions are satisfied, but deviations are commonly observed in ecological data and are sometimes also used in ecological studies (Bolker et al., 2009; Schielzeth et al., 2020; Zuur et al., 2009). Hence, after confirming that no alternative models (e.g., through transformations) improved fit or resolved deviations, I proceeded with the original LMM. Lastly, post-hoc pairwise comparisons were performed using estimated marginal means (emmeans package in R) with Tukey's adjustment (Lenth et al., 2025).

*Effect of mowing frequency, lupine density, and land cover type on lupine establishment.*

The establishment of new lupine plants was modeled using a Generalized Linear Mixed Model (GLMM) with a Poisson distribution to account for the response variable being count data. The model was fit using the `glmer()` function from the `lme4` package in R (Bates et al., 2015). Once again, the model accounts for repeated measurements from the same road by including road ID as a random effect. The response variable was the number of new lupine plants in each road segment. The predictor variables were mowing frequency (1-2), dominating land cover (factor: urban, agricultural land, open land, and forest) and lupine cover (the percent of the 500 m road segment covered by lupines). Due to some lupine stands not being perfectly parallel to the road, the lupine cover (%) occasionally exceeded 100%. To correct this overrepresentation, lupine cover greater than 100% were truncated to 100%. To facilitate analysis, lupine length percentage values were grouped into categories. Using the model described above, intervals of 10%, 20%, and 25% were tested, and the 20% interval was selected based on a comparison of model Akaike Information Criterion (AIC) values. Segments with a length of less than 495 meters were excluded from the analysis to prevent issues caused by partial segments created during point generation at 500-meter intervals. Additionally, road segments categorized as "urban" land cover were excluded due to a low number of observations ( $n = 4$ ). This improved model stability by solving numerical issues caused by the low observation count, which affected model convergence.

Model assumptions, including the normality of residuals and homoscedasticity, were evaluated using diagnostic tools from the `DHARMA` package (Hartig, 2024). These diagnostics revealed deviations from normality. Experiments with different link functions and variable transformations did not provide improvements. The original GLMM with the Poisson link proved to be the most suitable model. Multicollinearity between predictor variables was checked using variance inflation factors (VIF) from the `car` package (Fox et al., 2024). Pairwise comparisons between independent variables were performed using estimated marginal means (EMMs) from the `emmeans` package (Lenth et al., 2025). Tukey's method was applied to adjust significance levels for multiple comparisons.

Lastly, a Chi-square goodness-of-fit test was performed for both vegetation density and height (Table 1) surrounding the new individual lupine plants to determine whether the distribution of their respective categories followed an equal distribution. All statistical analyses were performed in RStudio (version 2024.09.1), and data visualizations were created using the `ggplot2` package (Wickham et al., 2024).

### 3 Results

#### 3.1 Change in lupine stand length over time

For the analysis of lupine spread, approximately 251,6 km roads were included (Figure 1). In 2021, the total length of all lupine stands was around 24 995 meters. By 2024, the total length had increased to approximately 31 275 meters, resulting in a total expansion of 6 280 m. On average, lupine stands expanded by 8.4 m in length between 2021 and 2024 ( $V = 13624$ ,  $p$ -value  $<0.005$ ). In addition to the established stands and lupine individuals, 209 new lupine stands were identified between 2021 and 2024, with the average length of these newly established stands being 15.2 m.

#### 3.2 Road verge management practices: frequency and alignment with lupine phenology

PEAB in Heby is responsible for mowing all state road verges within Heby/Sala municipalities. In 2023, a total of 314,0 km of road verges were mowed in the study area (representing the total length of roads, not the combined length of both sides) (Fig. 1). Of this, 238,7 km were mowed twice, with 22,9 km mowed during seed maturation (during week 27 -30) for the first cut and after seed release for the second cut (later than week 30). An additional 9,3 km were mowed after seed release for both cuts. Furthermore, 75,3 km were mowed once, with 69,9 km mowed during seed maturation and 5,5 km mowed after seed release. No mowing occurred before seed maturation (before week 27).

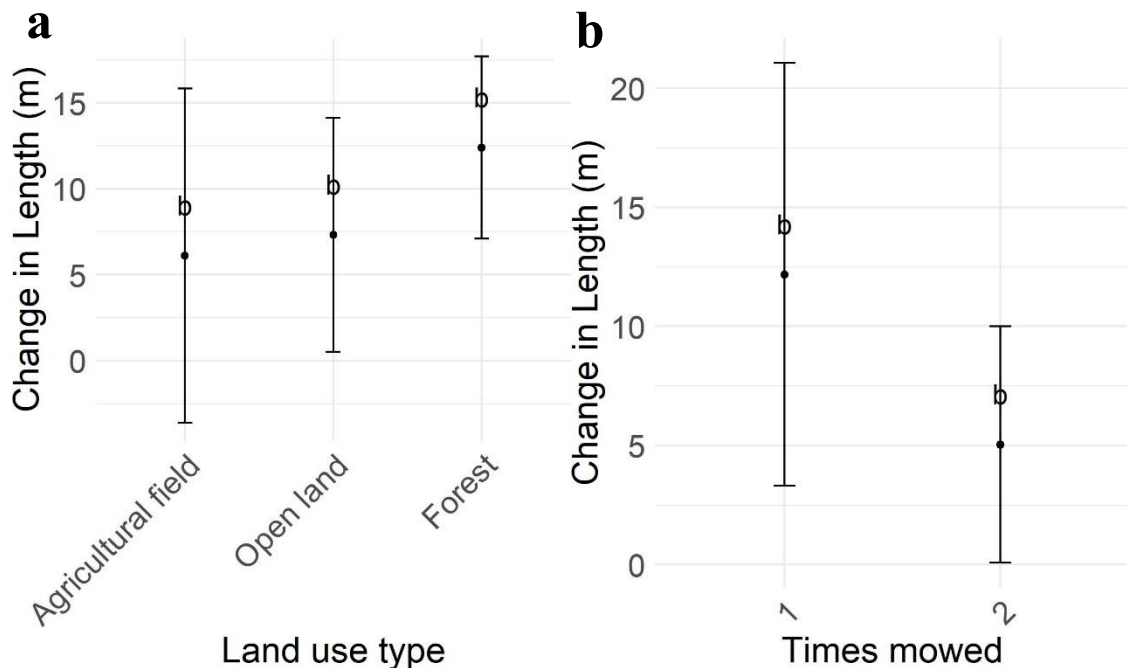
For all roads, the first cut was performed between weeks 27–35, while the second cut occurred between weeks 35–39. The first cut did not differ significantly across weeks in terms of single- vs. double-mowed roads. However, the largest stretch of the single mowed roads was cut in week 28 whereas most of the double mowed roads were first cut in week 30. (table 2)

**Table 2.** The timing of the first mowing for single- and double-mowed road verges within the study area in 2023. The table shows the total length of road verges (In meters, not the combined length of both sides) mowed for the first time in each week (week 28–35). Single mowing refers to road verges that were mowed only once during the season, while double mowing refers to road verges that were cut twice.

Week 1	Single mowing (meters)	Double mowing (meters)
28	51 875	41 438
29	1033	49 067
30	4329	96 966
32	0	5495
35	0	1427
<b>Total</b>	<b>57 237</b>	<b>194 393</b>

### 3.3 Influence of road verge management practices and land cover type on established lupine stand expansion

There was no statistically significant difference in lupine stand length change among different land cover types (agricultural land, open land, or forest) (Figure 4a), nor between single- and double mowed road verges. However, a trend suggested that lupine stands in forest road verges increased more in length, as well as stands along road verges that were mowed once (Figure 4b). The analysis was based on 529 observations.

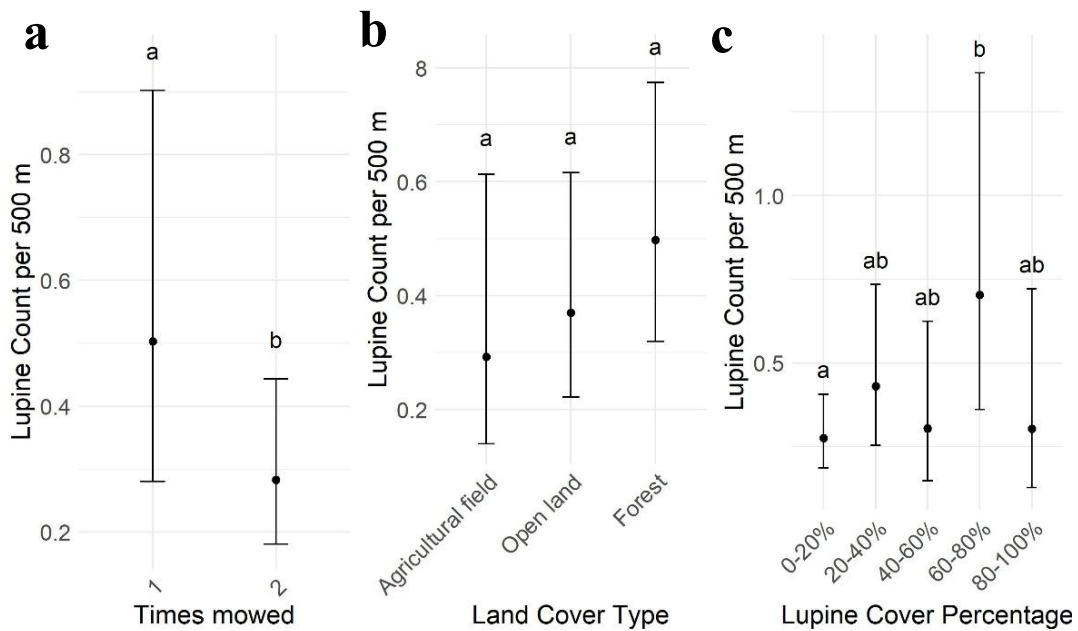


**Figure 4.** Estimated change in lupine stand length (m) (2021- 2024) across a) different land use types and b) mowing frequencies. Points represent estimated marginal means, with error bars showing 95% confidence intervals. Different letters indicate significant differences between groups, with groups sharing a letter not significantly different from each other.

### 3.4 Factors affecting establishment of new lupine individuals: mowing frequency, lupine cover, and landscape type.

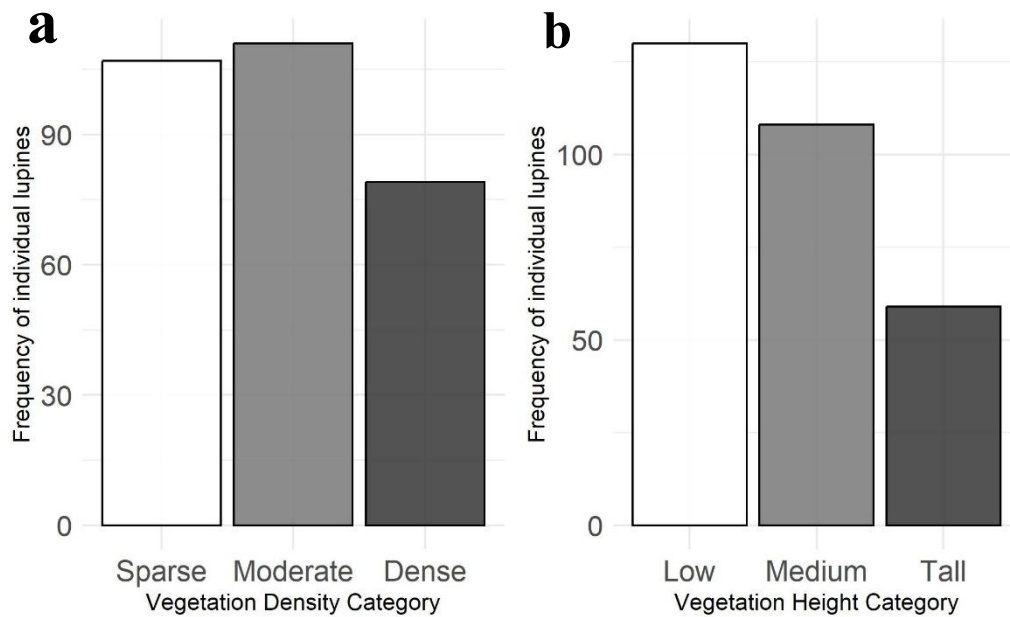
A total of 264 new single plants were found within the study area. Mowing frequency significantly influenced the establishment rates of new lupine plants. Road verges that were mowed twice were associated with significantly fewer new lupine plants compared to single-mowed road verges (Estimate = -0.574, SE = 0.244,  $p = 0.018$ ) (Figure 5a). Establishment of new lupine individuals among agricultural areas, open land, and forests showed no significant differences. (Figure 5b) The fixed effect for lupine cover (percentage cover of lupines on a 500 m road segment), showed significant variation in establishment rates. Road verges with 20–40% lupine cover had a higher establishment rate compared to the baseline category (0–20%; Estimate = 0.448, SE = 0.205,  $p = 0.029$ ). Similarly, road verges with 60–80% cover showed an even greater establishment rate compared to 0–20% (Estimate = 0.938, SE = 0.288,  $p <$

0.001). However, no significant differences were observed between other categories (e.g., 40–60%, 80–100%) (Figure 5c). No significant collinearity was detected between the independent variables.



**Figure 5.** Establishment rates of lupine individuals per 500 m road segment across a) mowing frequencies, b) land cover types (agricultural field, open land, forest), and c) lupine cover percentage on the same road segment (0–20%, 20–40%, 40–60%, 60–80%, and 80–100%). Points represent estimated marginal means, with error bars showing 95% confidence intervals. Different letters indicate significant differences between groups, with groups sharing a letter not significantly different from each other.

The distribution of individual lupine plants across vegetation density categories was significantly different from uniform ( $\chi^2 = 6.14$ ,  $df = 2$ ,  $p = 0.04639$ ). Standardized residuals indicated that “Moderate” and “Sparse” vegetation categories had more observations than expected, while “Dense” had fewer (Figure 6a). The distribution across vegetation height categories was also significantly different ( $\chi^2 = 26.69$ ,  $df = 2$ ,  $p < 0.001$ ). The “Low” height category had more observations than expected, while “Tall” had fewer and “Medium” showing no significant deviation (Figure 6b).



**Figure 6.** The distribution of lupine individuals differed significantly across both a) vegetation density ( $\chi^2 = 6.14$ ,  $df = 2$ ,  $p = 0.046$ ) and b) height categories ( $\chi^2 = 26.69$ ,  $df = 2$ ,  $p < 0.001$ ).

## 4 Discussion

### 4.1 Key findings and their implications

The results of this study provide evidence of a continued and substantial spread of *L. polyphyllus* along the 251,6 km roads within the study area. The average increase of 8.4 meters per stand suggests that road verge conditions continue to facilitate lupine expansion. The establishment of over 264 new lupine individuals highlights not only the expansion of established lupine stands but also successful establishment of new areas along road verges. These findings strengthen concerns about the species' long-term impacts on roadside ecosystems. It also suggests that its spread has not been halted by the current road verge management techniques, which are not primarily aimed at controlling IAPs. Even in managed landscapes, IAPs are difficult to control, as evidenced by findings from other regions. Over the course of 18 years (1998- 2016) Klinger et al. (2019) documented the spread of lupines in the Rhön UNESCO Biosphere Reserve and discovered that the invaded area roughly doubled. Their study area, like my study area, was managed by local authorities, though the mowing dates were unknown. Similar patterns have been observed along the Patagonian Paloma River, where lupine stands became denser between 2007 and 2010, although the expansion was less pronounced (Meier et al., 2013).

Mowing within the study area did not follow the most effective timing for limiting lupine spread and may even have contributed to the rapid expansion observed. Mowing before

seed maturation is recommended for preventing seed dispersal from established lupine stands (Klinger et al., 2020; Ludewig et al., 2022). However, within the study area, mowing during this critical window was non-existent. The first mowing mostly took place during seed maturation and no mowing occurred before seed maturation. Late-season mowing likely facilitated seed dispersal, as mowing machinery is thought to aid lupine seed dispersal by transporting seeds over long distances (Lennartsson et al., 2021; Tschan, 2018; Wissman, 2015). Furthermore, variability in mowing execution, particularly on single-mowed road verges, further complicates control efforts. It's possible that the first mowing may have focused on inner slopes, leaving other sections uncut until the second mowing (Trafikverket, 2024c). Consequently, uncut areas could have served as refuges for lupines to continue seed production and dispersal.

Based on my findings, double mowing was more effective than single mowing in reducing lupine establishment, but it did not significantly limit the expansion of already established lupine stands. Previous research has also noticed the role of mowing frequency in limiting seed dispersal (Jantunen et al., 2007a). Jantunen et al. (2007) found that seed production success was higher on single-mowed road verges compared to double-mowed road verges, explaining that less frequent mowing may allow for greater seed production and dispersal. The low effect of double mowing on the expansion of established stands can be explained by the resilience of larger plant populations. These mature populations have higher seed production and a better ability to regenerate (Elam et al., 2007). My results are also similar to an experiment conducted in Frösaråsen, showing that mowing twice per year for three years inhibits new lupine establishment (with seed dispersal), but doesn't limit the expansion of already established stands (Wissman, 2015). While Ramula (2014) found no direct link between lupine population size and vital rates, the same study showed that vital rates in lupines increase with plant size, further supporting the persistence of older populations. Although mowing before seed maturation can reduce the establishment of new plants, existing stands may still contain a seed bank that enables regrowth after mowing. Since mowing does not directly impact seeds in the soil, new plants can continue to emerge over time. My study suggests that to prevent human-mediated seed dispersal along road verges, mowing frequency should increase and should also be better synchronized with lupine phenology.

Adjacent land cover type did not significantly influence lupine expansion or the rate of lupine establishment. This finding is consistent with previous studies (Ramula, 2020) and most likely because lupines are already established in a wide range of regions and environments (Eckstein et al., 2023). However, trends in my data suggest that road verges adjacent to forests could offer conditions that favor lupine establishment and expansion. Several factors could explain the trend seen in road verges going through forested landscapes. Firstly, forested areas within the boreo-nemoral zone of Heby and Sala municipalities are partly characterized by moderately dry and nutrient-poor soils (Diekmann, 1994). Dry conditions could be favorable for lupines because their habitat tolerance exceeds that of competing plant species (Vetter et al., 2019). However, broad conclusions involving soil conditions along road verges can be difficult to make due to the influence of excavation material deposited during road construction (Tschan, 2018; Wissman, 2015).

Secondly, road verges adjacent to forests have lower and less dense vegetation due to limited light availability (Bogren, 1991). When reducing the light-competition among plant species, it could create favorable conditions for lupines. The establishment of lupines along species-rich road verges is affected by competition from native vegetation (Daniel-Ferreira et al., 2024). Even though my study included all state roads (not only species-rich), this could help explain a lupine preference for road verges adjacent to forests. Furthermore, management history of forested areas could impact the result. Past disturbances can create favorable conditions for invasive species. For example, Altamirano et al. (2016) found a direct correlation between the presence of the invasive fabacean species *Ulex europaeus* and proximity to forest plantations in Chile. This suggests that similar patterns could influence lupine establishment. Additionally, detection bias cannot be ruled out. Lupines might simply be easier to observe in areas with sparse vegetation. This would make them easier to detect along road verges adjacent to forests. During my field inventory, this was a pattern I noticed.

Urbanization is often linked to the spread of IAPs. León Cordero et al. (2016) found a positive correlation between the presence of the fabacean IAPs *Ulex europaeus* and urban areas along road verges in Brazil, and similar patterns have been observed for *Genista monspessulana* in Chile (García et al., 2014). However, the sample size of urban environments in this study was too small to assess their influence. Incorporating land use classification during field surveys could improve accuracy and reveal patterns that were not detectable due to the small sample sizes of urban land.

Lastly, the results of this study indicate that already established lupine stands along road verges can contribute to a higher establishment rate of new lupines nearby. Similar lupine patterns have been in the Rhön UNESCO Biosphere Reserve (Klinger et al., 2019). This also supports conclusions that IAPs spread through both nucleation (established populations facilitate establishment by creating improved growth conditions) and seed dispersal (Christen & Matlack, 2009; Pauchard & Alaback, 2004). However, the relationship between lupine cover and the rate of establishment of new lupine individuals was not linear. The highest establishment rates were found in segments with moderate lupine cover. Road segments of 500 m with 20–40% and 60–80% cover showed a higher establishment rate of new lupine plants compared to the baseline category of 0–20%. In contrast, no significant increase in establishment was observed for segments with 40–60% or 80–100% cover. The low establishment rate in the highest cover category is expected, as full coverage simply gives no space for the emergence of new plants. In contrast, the lack of increased establishment in the 40–60% cover category is less intuitive and suggests that additional factors, such as local variations, may influence lupine establishment. Furthermore, methodological inconsistencies in cover estimation could have contributed to variations in the results. Since the polylines of lupine stands used to measure lupine cover were not always perfectly parallel to the road, some segments may have been misclassified due to over- or underestimation of lupine stand length.

It is worth considering a possible detection bias during inventories. The significant finding that lower surrounding vegetation density and height favored the establishment

rate of lupine individuals could be influenced by the difficulty of detecting lupines in dense and tall vegetation. However, light availability and competitive pressure from surrounding vegetation could also explain some of these patterns. My results discussed above also indicate that lupine establishment is higher along road verges adjacent to forests, where vegetation tends to be less dense and shorter. This raises the question whether it is the forest environment itself (e.g. shade or soil conditions) or the vegetation characteristics (lower density and height) that primarily affect lupine establishment along these road verges.

## 4.2 Future directions and broader implications

The decision was made to exclude “new” lupine stands detected in the 2024 inventory that were not recorded in the 2021 inventory in the analysis. These stands do not fall into either of the categories “established lupine stands” or “new lupine stands/or individuals,” as their origin is uncertain. There are two possible explanations for their presence: 1) they were simply missed during the 2021 inventory, or 2) they were newly established after 2021 and have since grown into a group of lupine individuals. Due to the uncertainty between these two scenarios, these stands were omitted from the analysis. Since it is impossible to determine when these stands were established, they could not be included in the analysis of lupine expansion or the rate of establishment. However, this uncertainty also could apply to individual lupines, as unfavorable conditions might have prevented them from expanding from a single individual into a larger stand. It is important to note that, while my results indicate a spread of lupines within the study area, the exclusion of these “new” lupine stands could potentially underrepresent the true extent of this expansion.

It would be valuable to examine unmown verges in more detail to determine whether these areas differ significantly in terms of lupine expansion and dispersal from single- and double-mowed road verges within the study area. Such an analysis could help clarify whether mowing practices have effectively limited lupine spread or, conversely, contributed to its acceleration. However, assessing unmown road verges in urban areas where humans live and act in their daily lives presents several challenges. While state and municipal road verges follow regulated mowing practices, unmown verges are often the ones found along private roads that are managed by individual landowners. These private landowners likely use varying approaches to IAPs management, including lupine control. Although removing IAPs is required by law, lupines are not yet subject to this regulation (Naturvårdsverket, 2022). Nonetheless, it is generally advised to remove lupines since they are widely recognized as an IAPs in Sweden (Naturvårdsverket, 2022). For example, residents in Heby municipality are encouraged to remove lupines through events such as the national "Lupine picking day" (Swedish: lupinplockardagen) on June 6th (Nord, 2024b). Some private road owners find lupines to be aesthetically pleasing despite these recommendations, and they are not aware by the ecological impact (Wissman, 2015). Private road verges probably have a wide range of management techniques, depending on personal beliefs and expertise. This variation was evident in field observations, as severable sizable lupine stands that had been documented in 2021 were absent from the 2024 inventory close to certain farms. Active removal efforts likely

contributed to these declines. On the other hand, some households had some of the largest and most dense lupine populations observed in the study area. These differences pinpoint the influence of individual landowner decisions on lupine management and the challenges of implementing consistent control strategies on private roads.

Roadside management/Mowing frequency and timing plays a big role in both IAPs management and biodiversity conservation. While there are some recommendations for management of road verges for IAPs control, these are not always aligned with recommendations for promoting overall biodiversity. Mowing 0-2 times per season is generally advised for species richness and pollinator density (Phillips et al., 2020). Contradictorily, the guidelines for IAPs control usually call for mowing at least twice per season (Fremstad, 2010; Naturvårdsverket, 2022). In Sweden, mowing once later in season has been demonstrated to support higher plant densities than mowing twice in early summer and autumn (Horstmann et al., 2024), underscoring the significance of both the mowing timing and frequency for biodiversity. However, there are also differences in the timing of mowing between the two goals: mowing should take place early in the season, prior to seed maturation, for IAPs control (Eckstein et al., 2023; Klinger et al., 2020), while later mowing is usually advised for promoting plant species richness (Naturvårdsverket, 2024). My results indicate that mowing twice per year can suppress the establishment of new lupine plants compared to mowing once. This aligns with what is generally recommended for managing invasive species, but it does not necessarily help broader biodiversity goals. One solution to this dilemma might be to focus on road verges that are already dominated by IAPs, like *L. polyphyllus*, to keep them from spreading into areas with higher biodiversity. By focusing on these high-risk zones, management efforts could be more effective in hindering the expansion of invasive species while minimizing disruption to ecologically valuable road verges. However, a complication factor is that lupine seeds are often present in the seed bank of many road verges, making such a distinction difficult in practice.

One important question for future studies is how and to what extent mowing contributes to the spread of lupine seeds. As my study and others have suggested, mowing machinery during seed maturation may facilitate seed dispersal (Eckstein et al., 2023; Tschan, 2018). Knowledge about how seed dispersal and establishment rates are affected by mowing practices will benefit the development of mowing techniques. Compounding these challenges, climate change along with urban development is expected to intensify the spread of IAPs which include *L. polyphyllus*. This highlights the importance of developing effective methods for IAPs management, before the problem becomes too widespread. Mowing practices re-adjusted to target lupines could reduce their establishment. However, it is also important to consider the potential impacts on biodiversity. If road verges were mowed primarily for lupine control, the frequency and timing of mowing could instead negatively affect species' richness.

## 5 Conclusions

The rapid expansion of *L. polyphyllus* along Swedish road verges shown by this study underscores the urgency of adaptive, evidence-based management. While mowing remains a cornerstone of IAPs control, its effectiveness depends heavily on precise timing and frequency. This study revealed a critical misalignment between current mowing practices along Swedish road verges and the recommended strategies for IAPs control, particularly the need to mow before seed maturation. The results indicate that in order to stop the spread of lupine in the future, it is necessary to update current mowing schedules and inform all stakeholders involved. This study also emphasizes the impact of land cover type on the expansion of lupine stands and in addition to mowing practices. Additionally, I suggest that lower and less dense vegetation potentially facilitate lupine establishment.

I propose that a few crucial measures be given top priority to lessen the ongoing expansion and establishment of *L. polyphyllus* along Swedish road verges. First, to limit dispersal and the establishment of new populations and lupine individuals, mowing schedules should first be modified to coincide with the time before seed maturation. Second, to identify and promptly act against new establishments, it is crucial to monitor both recently inhabited and lupine-free areas. Third, to stop the dispersal of lupines from lupine areas to lupine-free areas, mowing techniques must be modified. For example, machinery used in lupine areas should not be used in lupine-free areas without cleaning to avoid seed dispersal (Helldin et al., 2022). Lastly, balancing the control of *L. polyphyllus* with biodiversity conservation seems to be contradicting. Hence, it requires site-specific approaches. To achieve the above will demand collaboration across stakeholders, including municipal authorities, road maintenance agencies, and private landowners. However, the urgency of IAPs, including *L. polyphyllus*, management cannot be overstated. Delays in action will only worsen the challenges posed by this species, particularly as climate change and urbanization continue to alter the landscape.

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# Appendix

## Appendix A: : Land cover type classifications

Reclassification of Land Cover Types from Lantmäteriet's GSD-Topographic Map

Land cover type	Description (Category code)
Urban	Industrial area (15), High-rise buildings (13), Group of buildings with courtyard (12) Low-rise buildings (14)
Agricultural land	Arable land (4)
Open land	Other open land (5)
Forest	Forest, coniferous and mixed (2), Deciduous Forest (19)
Water	Water body (1)

## Appendix B: Glossary

Term	Description
Invasive alien plant species (IAPs)	Non-native plant species introduced by human activities that spread aggressively and cause harm to ecosystems, economies, or human health (Zimdahl & Brown, 2018).
IAPs spread	The introduction, establishment, expansion, and dispersal of invasive alien plant species, forming widespread populations that lead to ecosystem disruption (With, 2002).
Dispersal	The movement and establishment of plant propagules away from the parent plant, enabling the species to spread into new areas (Cousens et al., 2008).
Established lupine stands	Lupine stands (small, localized lupine populations) present during both first and second inventory (2021 and 2024).
Lupine stand expansion	The positive change in length of established lupine stands.

<b>Term</b>	<b>Description</b>
New lupine stands	Lupine stands found at the 2024 inventory (not present 2021).
Lupine individuals	A single lupine individual noticed during the 2024 inventory, outside of pre-existing stands.
Rate of establishments	The number of lupine individuals established on a 500 m road verge segment.
Lupine cover	The proportional length (%) of all lupine stands along a 500 m road segment.