

**ECOLOGICAL CHARACTERISTICS AND ECONOMIC IMPACT OF NON  
NATIVE *Ailanthus altissima* (MILL.) SWINGLE IN HESSE, GERMANY**

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## ABSTRACT

The introduction of alien species into new environments for many centuries has led to global biodiversity impacts which have been altering ecological processes gradually. These alterations include the extinction of species and even the endangering of valuable ecosystems as well as an irrational increase in the economics and cost controls.

One of the reasons for species introduction is the growing need for using them as timber, medicinal plants or food. Other species have been introduced for purely scientific purposes so escaping cultivation and becoming real problems in the ecosystems where they are included. This is the case of *Ailanthus altissima* (Mill), swingle (ailanto or “tree of heaven”), Quassia family (Simaroubaceae).

More than 200 years ago, *Alianthus* was introduced in Europe where it has been causing serious damage due to the size and strength of its roots which are able to break up walls, foundations, water pipes, sewage systems, roads and rails. Thanks to its strong competitive ability and to its production of allelopathic substances, this plant limited and displaced native species. Apart from that, its pollen and chemicals are capable of producing allergies and, in some instances, poisoning deaths.

This research studied the distribution and dispersal of *A. altissima* in a rural-urban gradient and its distribution and frequency in the train stations in Hesse, Germany. The eco - physiological characteristics of the species were analyzed after planting them in different types of substrates and seed densities. The population dynamics was analyzed and determined by comparing plots within the city and outskirts, by interviewing managers of green areas, parks and cemeteries; private company directors and the Central German Train Company directors as well as physicians of the Allergy Centre. Then, the damage and population control cost of this invasive species was determined.

The results show that *A. altissima* is an urban species, although this condition does not exclude its presence in natural ecosystems where plant uses open space left by natural or anthropogenic disturbances. The eco-physiological characteristics were identified through the species' pioneer ability to colonize with rapid growth (1 or 2 m.y<sup>-1</sup>), versatility, adaptation and mass seed production (300000 to 1 million seed.y<sup>-1</sup>), combined with a vegetative success reproduction. For all these reasons *Ailanthus* has become a successful invasive plant species in Europe.

In Hesse, *Ailanthus* was found more frequently associated with neighbourhoods and open areas near cities, but less frequently in parks and cemeteries. Its absence in the Taunus region reminds us of an apparent limitation caused by the exclusive competition caused by shade tolerant

species present in this place. In North Hesse, where climatic conditions are apparently different, *A. altissima* was found less frequently.

The distribution map generated from the results of this study shows that *A. altissima* is more abundant in cities with highest human population. This suggests a dependence on population density and traffic because winged-seeds are easily blown by the movement of automobiles and trains in these areas.

*Ailanthus altissima* was more frequent and abundant at big size stations with greater movement of trains and people, especially in the southern part of Hesse, and in the Frankfurt, Wiesbaden, Hanau and Darmstadt stations. This suggests a dependence on the station size and substrate type.

*Ailanthus altissima* has a high germination rate in all types of substrate, especially when planted in bare soil, followed by soils with gravel, which explains its growth near the train stations where gravel accumulates at the edge of the rails. When the seeds fall into the grass-covered soil, the germination rate drops drastically, and there is no germination at all.

The increase in population density appears to stimulate seed germination rate and plant elongation in substrates such as bare soil and gravel. Root development decreases with increasing seed density on bare soil. The opposite was observed in gravel. Similar results were obtained with the basal stem diameter and wet and dry plant weight.

The population dynamics study demonstrated that the population growth rate of *Ailantus altissima* located in the centre and outskirts of the city is very high. Although in the city pruning is more frequent, the controls do not appear to be effective due to the abundance of seed-producer trees. The amount of seeds, the high germination rate and the yearly survival of this species produced a great increasing growth rate of the population.

Every year, *A. altissima* produces a large number of new individuals (530,000 - 560,000). Seedlings can grow one or two meters during its first year of life. Once the plant reaches this stage, it is more difficult to control especially for the large number of re-sprouts produced after cutting and for its high survival rate during this period. Once the plant reaches 3- or 4- year old, it begins to produce seeds (less than 80,000 per year). The higher seed production is reached by 10- to-12 year old trees with a production of 300,000 to 1,000,000 seeds per tree per year.

According to the results of this study, management and control of the *A. altissima* population should include the pruning of mature trees dbh > 10 cm (vital stage in the reproductive cycle), especially during the seed production period, i.e. June and July, with emphasis on cutting branches with abundance of seeds.

Costs incurred by the control of *A. altissima* in Hesse, represent 5 million Euros per hectare per year. Control management is threefold: physical, chemical and thermal. Chemical control is cheaper, although in Europe is highly restricted in order to preserve biodiversity prevent and to avoid soil

and water pollution. Physical control is more common and frequent; but its implementation has not succeeded in controlling the population growth of the above mentioned species. It includes a combination with chemical products under strict security controls. Once or twice a year, thermal control (along with some chemicals) is used by the German Train Company to avoid the growth of species near the rails.

For technical, economic and social reasons, the recommendations of this study are based on the use of physical control applied during the vital life-cycle stages of *A. altissima*, so that in a couple of years the population growth of the species is stabilized. For social reasons, personnel recruitment is recommended for carrying out this control which will create more jobs. With regard to biology, physical control is more appropriate to protect the diversity of species. Furthermore, the planting of grass on the banks of the rails should prevent the germination and growth of *A. altissima*.

## ZUSAMMENFASSUNG

Seit vielen Jahren ändern fremden Arten (Neophyten) Ökosysteme und Ökologische Prozessen. Diese Einflüsse sind z.B. die Ausrottung heimischer Arten, die Bedrohung wertvoller Ökosysteme und eine übermäßige Zunahme der Kosten die Ausbreitung dieser Pflanzen zu verhindern.

Ein Grund für die Einfuhr dieser Arten ist die wachsende Nachfrage nach Nutzpflanzen, die für Holz, Medizin oder Nahrung verwendet werden können. Andere Arten wurden nur aus wissenschaftlichem Interesse gehalten, entkamen aber ihrer Obhut. Auf freier Wildbahn wurden sie zu ernst zu nehmenden Problemen. Der trifft auch für Götterbaum *Ailanthus altissima* aus der Familie der *Simaroubaceae* zu.

*A. altissima* wurde vor über 200 Jahren in Europa eingeführt und hat seitdem zu starken Schäden in die Stadt geführt, da die Wurzeln so stark sind, dass sie Wände, Fundamente, Abwasserleitungen, Straßen und Schienenwege durchbrechen können. Aufgrund der Konkurrenzstärke und der Produktion von allelopathischen Substanzen ist die Pflanze in der Lage einheimische Arten zu verdrängen. Außerdem verfügt *A. altissima* über stark allergene Pollen die zu Vergiftungserscheinungen führen können.

Mit dieser Studie wurde in Hessen die Verteilung und Ausbreitung von *A. altissima* eines Stadt-Land Gradienten untersucht durch die Grafen von

Individuen in drei Größenklassen [(1) Jungpflanzen und kleine Bäumchen: 1cm Höhe - 1cm Durchmesser von 1,3 m über dem Boden, dbh), (2) große Setzlinge und Jugendliche: 1 cm dbh - 10 cm dbh und (3) Bäume > 10 cm dbh] in einem Gradienten rural - urban, wo die Stadt Frankfurt und dem Taunus aufgenommen wurden, um zu überprüfen, ob es Unterschiede in der Verteilung im Hinblick auf den Verlauf, die Verteilung und Häufigkeit in den Bahnhöfen in Hessen zur Karte Verteilung der Arten. *A. altissima* wurde auf verschiedenen Substraten (Normale Boden, Kies, Boden mit grass gepflanzt werden), und mit unterschiedlicher Samenmenge (100, 150 und 200 ind.m<sup>-2</sup>) gepflanzt und daraufhin auf physiologische hin untersucht um festzustellen, ob es Unterschiede in der Keimung und Wachstum in verschiedenen Arten von Substraten, analysierte auch die intraspezifische Konkurrenz in verschiedenen Pflanzendichten von Individuen,

Die Populationsdynamik wurde mit der Untersuchung von Flächen in der Stadt und am Stadtrand untersucht mit Hilfe von Lefkovitch Matrix. Außerdem wurden Interviews mit Landschafts- und Friedhofsgärtnern, Unternehmern, Vorsitzende der Deutschen Bahn und Allergologen durchgeführt, um das Ausmaß der Gefährdung und der Kosten der Eindämmung von *A. altissima* zu ermitteln.

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Die Ergebnisse zeigen, dass *A. altissima* eine städtische Art kommt aber auch in natürlicher Umgebung vor, wo sie offene Flächen nutzt, die auf natürliche oder anthropogene Einflüsse zurück zu führen sind. Vor allem das schnelle Wachstum, die Anpassungsfähigkeit und die Produktion von einer

großen Samenmenge, kombiniert mit der Konkurrenzstärke gegenüber einheimischen Pflanzen, führen zum Kolonisationserfolg von *A. altissima*, der sich quer durch Europa zieht.

In Hessen wurde *A. altissima* eher in der Umgebung von offenen Flächen in Stadtnähe gefunden, aber seltener in Parks und auf Friedhöfen. Die Abwesenheit in der Taunus-Region lässt sich auf die ausschließende Konkurrenz durch den Schatten-toleranten Pflanzen, die dort vorkommen, zurückführen. In Nord-Hessen, wo andere klimatische Verhältnisse herrschen, kam *A. altissima* seltener vor.

Eine regionale Verbreitungskarte von *A. altissima*, die für diese Studie angefertigt wurde zeigt, dass die Pflanze am häufigsten in Städten mit vielen Einwohnern vorkommt. Das zeigt, dass wohlmöglich ein Zusammenhang zwischen der Populationsdichte und dem Verkehr besteht. Durch den Fahrtwind der Autos und Züge werden Samen über weite Strecken in zufällig diese Regionen getragen.

*Ailanthus altissima* trat in der Nähe von großen Stationen mit vielen Personen und Zügen häufiger und verbreiteter auf. Dies besonders an Bahnhöfe in Süd-Hessen, wie Frankfurt, Hanau und Darmstadt. Das könnte bedeuten, dass die Größe eines Bahnhofs eine Rolle spielt, sowie der Bodentyp, der in dessen Umgebung zu finden ist.

*Ailanthus altissima* hat in allen Substrat-Typen eine hohe Keimungsrate. Besonders hoch ist die Keimungsrate auf normale Boden, gefolgt von



Schotter. Dies könnte erklären, warum die Pflanze an Bahndämmen so häufig vorkommt, da diese mit Steinen aufgeschüttet sind. Auf Grasflächen hingegen sinkt die Keimungsrate dramatisch auf den Nullpunkt.

Eine höhere Samendichte scheint die Keimungsrate zu erhöhen und größere Pflanzen in Substraten wie normaler Boden und Schotter zur Folge zu haben. Auf dem nackten Boden nahm die Wurzeldichte mit zunehmender Samendichte ab. Bei Kiesel-Böden ist der Effekt genau umgekehrt. Ähnliche Ergebnisse konnten mit dem basalen Stammdurchmesser und der feuchten und trockenen Biomasse erfasst werden.

Die Untersuchung der Populationsdynamik zeigt, dass die Wachstumsrate bei Populationen im Stadtzentrum und am Stadtrand sehr groß ist. Obwohl die Pflanzen in der Stadt zurückgeschnitten werden, scheint diese Kontrolle keinen Effekt zu haben, da die gestutzten Pflanzen eine höhere Samenproduktion aufzeigen. Die hohe Anzahl an Samen, der große Keimungserfolg und die große Konkurrenzstärke, führen zu einer großen Steigerung der Wachstumsrate der Population.

*Ailanthus altissima* erzeugt eine große Zahl an Nachkommen (zwischen 530.000 und 560.000 Setzlingen pro Jahr). Die Setzlinge können im ersten Jahr zwischen einem und zwei Metern wachsen. Hat eine Pflanze erst mal diesen Höhestatus erreicht, ist sie, aufgrund der hohen Anzahl an Neutrieben nach Beschneidungsaktivitäten schwieriger zu kontrollieren. Der Höhepunkt der Samenproduktion ist nach zwölf Jahren erreicht mit 300.000 bis 1.000.000 Samen pro Baum und Jahr.

Diese Ergebnisse legen nahe, dass adulte *A. altissima* Bäume ab einem BHD (Brusthöhendurchmesser) von 10 cm zurücksgeschnitten werden sollten. Dieses Stadium ist besonders in der Wachstumsphase zwischen Juni und Juli für den Reproduktionszyklus entscheidend.

In Hessen belaufen sich die Kosten innerhalb des Managements von *A. altissima* auf mehr als 5 Millionen Euros im Jahr. Zur Vermeidung der Ausbreitung werden im Wesentlichen physische, chemische und thermale Maßnahmen eingesetzt. Die chemische Methode ist kostengünstiger, sie ist aber in Europa stark beschränkt, um Verschmutzungen zu vermeiden. Die physikalische Methode wird häufiger angewandt, allerdings hat ihr Einsatz nicht zu einer Eindämmung des Populationswachstums geführt und sie erfordert einen zusätzlichen Einsatz von Chemikalien, die unter strengen Auflagen stehen. Die thermische Methode wird vor allem von der Deutschen Bahn durchgeführt, die ihre Schienenstränge ein bis zwei Mal im Jahr in Kombination mit Chemikalien behandelt. Sie zeigt bessere Ergebnisse in der Eindämmung der Pflanzen.

Zusammenfassend ist festzustellen, dass aus technischer sowie ökonomischer Sicht ein Zurückschneiden der Bäume innerhalb der Wachstumsphase einen entscheidenden Einfluss auf die Populationsregulation hat. Das Zurückschneiden ist auch aus biologischer Sicht sinnvoll, da es schonend mit anderen Arten umgeht. Darüber hinaus befürworten wir eine Anpflanzung von Gräsern an Bahndämmen vor, um eine Keimung von *A. altissima* an Bahnhöfen zu verhindern.

## RESUMEN

La creciente introducción de especies exóticas en nuevos ambientes ha producido, desde hace muchos siglos, impactos a la biodiversidad alterando procesos ecológicos con consecuencias devastadoras como la extinción de especies y en la transformación de ecosistemas de gran valor y un irracional aumento en los costos económicos del control.

Una de las razones de las introducciones de especies es la creciente necesidad del uso de especies vegetales para la generación de bienes y servicios, tales como madera, medicina o alimentos. Otras especies han sido inicialmente introducidas con fines meramente científicos pero han escapado al cultivo y se han convertido en verdaderos problemas en los ecosistemas donde han incurrido. Este es el caso del Árbol del cielo o Ailanto (*Ailanthus altissima*) (Mill) Swingle, el cual pertenece a la familia de las Quassias (Simaroubaceae).

Desde hace más de 200 años, el Alianto fue introducido en Europa donde ha venido causando graves daños, debido a que el tamaño y fortaleza de sus raíces son capaces de romper cimientos, acueductos y alcantarillados, carreteras y levanta rieles. Gracias a su fuerte capacidad competitiva y la producción de sustancias inhibidoras, esta especie limita y desplaza a las

especies vegetales nativas y su polen y sustancias químicas pueden producir alergias y, en algunos casos, envenenamientos a las personas.

Se estudió la distribución y abundancia de *A. altissima* mediante conteos de individuos en tres clases de tamaño [(1) plántulas y brinzales pequeños: 1cm de altura - 1cm de diámetro a 1.3 m altura del pecho, dap), (2) brinzales grandes y juveniles: 1cm dap - 10cm dap y (3) árboles: > 10cm dap] en un gradiente rural – urbano que incluyó la ciudad de Frankfurt y el bosque del Taunus para comprobar si hay diferencias en la distribución con respecto al gradiente, su distribución y frecuencia en las estaciones de tren en Hesse para elaborar mapas de distribución de la especie. Se analizó su comportamiento fisiológico al ser sembrado en distintos tipos de sustratos (suelo desnudo, suelo con grava y suelo con grama) para establecer si hay diferencias en la germinación y crecimiento en los diferentes tipos de sustratos, además se analizó la competencia intraespecífica sembrando en diferentes densidades de individuos (100, 150 y 200 ind.m<sup>-2</sup>, se estudió la dinámica de su población usando matrices de Lefkovitch comparando parcelas dentro y en las afueras de la ciudad para establecer diferencias en las tasas de crecimiento poblacional con aplicación de controles. Finalmente, a través de entrevistas a directores de áreas verdes, parques, cementerios, empresas privadas como la compañía central de trenes alemana y directores médicos se estimaron los daños ocasionados y los costos del control de las poblaciones de esta especie invasora.

La abundancia de *A. Altissima* fue mayor en áreas urbanas que fuera de esta; eso la confirma como una especie urbana por excelencia. Sin embargo, no se excluye su presencia en sitios de vegetación natural donde aprovecha los espacios abiertos por alteraciones naturales o antropogénicas para colonizar. Logra esto gracias a su rápido crecimiento, versatilidad, adaptación y masiva producción de semillas propia de las especies pioneras combinada con una reproducción vegetativa vigorosa.

En Hesse, *Ailanthus* fue encontrada con mayor frecuencia asociada a los vecindarios y en áreas abiertas cerca de las ciudades y, en menor escala, en parques y cementerios. Su ausencia en la región del Taunus sugiere en una aparente limitación causada por la competencia exclusiva ocasionada por especies presentes en el lugar que generan sombra y ocupan dichas áreas. En el norte de Hesse menos urbano y más fresco, donde las condiciones climáticas aparentemente son diferentes a las encontradas en las ciudades, *A. altissima* fue encontrado con menor frecuencia que en el sur.

El mapa de distribución muestra que *A. altissima* se encuentra en mayor abundancia asociado a las ciudades con mayor población humana. Esto sugiere una dependencia de la densidad poblacional y puede deberse a un mayor movimiento vehicular y de trenes, ya que es muy probable que las semillas aladas sean fácilmente transportadas accidentalmente por autos y en los rieles de los trenes en estas zonas.

*Ailanthus alitissima* se encontró con mayor frecuencia y mayor abundancia en las estaciones con mayor movimiento de trenes y personas, especialmente en la zona sur de Hesse, en las estaciones de Frankfurt, Wiesbaden, Hanau y Darmstadt. Este resultado sugiere una dependencia de la especie a estaciones de mayor área y muy probablemente del tipo de sustrato presente en éstas.

*Ailanthus altissima* presenta una alta tasa de germinación en todo tipo de sustrato, en especial cuando se siembra en suelo desnudo, seguido de suelos con presencia de grava. Lo anterior explica el crecimiento de esta especie cerca de las estaciones de tren donde se ha observado creciendo en la grava depuesta a la orilla de los rieles. Cuando las semillas caen en suelo con presencia de hierba o grama, la tasa de germinación desciende drásticamente e incluso las semillas no germinan.

El aumento en la densidad de semillas parece estimular la tasa de germinación y la elongación de la planta en sustratos como suelo desnudo y grava. El desarrollo radicular disminuye con el aumento de la densidad de semillas en el suelo desnudo, lo contrario se observa en suelos con grava. Similares resultados se obtuvieron con el diámetro basal y biomasa de la planta.

La tasa de crecimiento de las poblaciones ubicadas en el centro y en las afueras de la ciudad es muy alta  $>10$ ; a pesar de que en la ciudad las podas son más frecuentes, los controles parecen no ser efectivos debido a la mayor abundancia de árboles productores de semillas. El gran número de semillas producidas, la alta tasa de germinación y sobrevivencia de esta especie, ocasiona cada año un aumento considerable en la tasa de crecimiento poblacional.

*Ailanthus altissima* produce cada año entre 530000 y 560000 plántulas que crecen 1 – 2 m de altura total en su primer año de vida. Una vez superada esta etapa, la planta es más difícil de controlar debido al gran número de rebrotes producidos luego del corte y a la alta tasa de sobrevivencia en este período. Una vez alcanzado los 3 o 4 años de edad, los árboles jóvenes empiezan a producir semillas (menos de 80000 semillas/ año). La mayor producción de semillas se alcanza en los árboles de 10 – 12 años con un número que varía entre 350000 y 1000000 semillas/árbol/año.

Se recomienda que para el manejo y control de la población de *A. altissima* se debe podar los árboles adultos (dap  $> 10$  cm, etapa vital en el ciclo reproductivo), especialmente en el período de producción de semillas (entre Junio y Julio), cortando las ramas con mayor abundancia de semillas.

El estudio de los costos ocasionados por el control de *A. altissima* revela que en Hesse, se gastan más de 5 millones de Euros por año. El manejo incluye tres tipos de control: químico, físico y termal. El control químico (aplicación de herbicidas) es más económico, aunque en Europa está altamente restringido para evitar daños en la diversidad y contaminación de suelos y agua. El control físico a través de la poda es más común y frecuente, su aplicación no ha logrado controlar el aumento poblacional de la especie y requiere la combinación con productos químicos bajo estrictos controles de seguridad. Así mismo, el control termal aplicando fuego directo y con máquinas de vapor es usado por la compañía de trenes alemana una o dos veces al año combinado con químicos (herbicidas) para lograr un mejor control de *A. altissima* y otras especies que proliferan a orillas de los rieles.

Por razones técnicas, económicas y sociales, nuestra recomendación se basa en el uso del control físico por su carácter amigable con la naturaleza, usando la poda en las etapas cruciales el ciclo de vida de *A. altissima*, esto es sobre los árboles maduros para reducir el crecimiento poblacional de la especie. Además desde el punto de vista social la aplicación de podas garantiza la contratación de personal para realizar el control. También se recomienda sembrar grama a orillas de los rieles para evitar la germinación y crecimiento de *A. altissima* en las estaciones.



# **CHAPTER 1**

## **1. General Introduction**

### **1. Invasive Species History**

The invasion of exotic plant species into other regions which were previously separated by bio-geographic barriers is one key problem of land use and land-cover change (D'Antonio & Vitousek 1992). Frequently, plant species are introduced into new areas because of the economic value they hold, such as crop species, timber trees, forage plants, and for ornamental use (Heywood 1989).

Alien plant species were introduced into Europe throughout history. There are regions, such as the Mediterranean, where for thousands of years people were responsible for the spread of ever-increasing numbers of plants and animals. The movement of alien plant species was mainly due to the need of food for consumption, for trade and for the survival of human communities. The improvement and greater efficiency of transportation along with the growing frequency of travel has facilitated, over time, the spread of imported species (Scalera & Zaghi 2004).

During the 18th century Europeans began to have an increasing interest in exotic species from all over the world resulting in intensive efforts to establish new viable specie populations. This new “fashion”, was linked to both socio-economic and ornamental reasons, which led to the foundation of specialized

“acclimatization” societies, such as the Société Impériale d’Acclimatisation founded in Paris in 1854 (Lever 1996) or the Acclimatisation Society of the United Kingdom.

Today, with the exceptional ease and speed with which people and goods move, the intentional and unintentional introductions of IAS became present and are vastly becoming directly related to various economic sectors – trade, tourism, agriculture, forestry and fisheries – since all has dramatically increased (Scalera & Zaghi 2004) within recent years.

In this manner, *Ailanthus altissima* has spread throughout Europe and England. It proliferated when it was discovered that a silkworm, *Samia cythia*, produced a high quality silk when grown on *A. altissima* leaves (Feret 1985, Frank 1986, Kowarik & Säumel 2007) as well as the rapid growth the tree exhibited. Its foliage was also considered beautiful by many Europeans (Hu 1979).

### **1.1.2 Definition and characteristics of invasive species**

#### **What is an invasive alien species?**

Some words are used as synonyms although they should not be; the common meaning of some terms is quite different from the technical meaning. The terms listed below agree with the definitions reported by IUCN (1995 and 2000), as well as those recommended by Lever (1996) and Richardson *et al.* (2000). Currently, a revision of the definitions and

terminology is being carried out by the European Council of Environment Ministers (Scalera & Zaghi 2004).

**Alien Species** A species, subspecies or lower taxon occurring outside of the historically known range it occupies naturally and outside its dispersal potential as a result of direct or indirect introduction or care by humans; includes any part, gametes or propagates that might survive and subsequently reproduce. Synonyms are non-native, non-indigenous, foreign, and exotic.

**Invasive Species** A species that is able to establish stable populations, colonizing irreversibly and spreading rapidly in entire natural or semi-natural ecosystems. Biological invasions may also be a natural phenomenon, determining natural range expansions or contractions, without direct interventions by humans, although sometimes they may be fostered by possible human related environmental changes.

**Non-native plant species** Are those that occur outside their native ranges in a given place as a result of actions by humans. The term non-native can be used interchangeably with the terms alien, exotic, introduced, and non-indigenous. Many groups of individuals include plants have the ability to leave their natural habitat and settle in new territories.

**Exotic Species** A species that is not native to a designated ecosystem or geographic area. Because some exotic species may be harmful or invasive

while others are not, this term should be used with great care. Synonyms include non-indigenous, non-native, foreign and alien species.

**Pest Species** A species which may spread and cause serious environmental changes so as to threaten the conservation of indigenous habitats and species or cause severe economic losses to human activities.

**Established Species:** A non-native species with a permanent, reproducing population that is unlikely to be easily eliminated through human action or natural causes.

**Acclimatized Species:** species living in the wild and in an alien environment or climate with the support (i.e. for food and shelter) of humans.

**Naturalized Species** An introduced or feral population of species established in the wild with free-living, self-maintaining and self-perpetuating populations unsupported by and independent of humans.

**Introduction** The process by which a species, subspecies, or lower taxon (including any part, gametes or propagules that might survive and subsequently reproduce) is transported by humans outside its historically known natural range, either intentionally or accidentally.

Biotic invasions are both intentional and accidental events that place formerly isolated species into contact with each other, faster than the normal rate of evolution (D'Antonio & Vitousek 1992).

The probability of a successful invasion corresponds to the type and degree of disturbance (street construction, gap, hurricanes, for example), the number of non-native propagules that arrived in the new habitat, the time period in which the community is exposed to the imported propagules (Rejmánek 1989), and the properties of the exotic species or the native species of concern (like seeds production, versatility, environmental resistance, growth rate, life strategies and others, Lonsdale 1999). Because such circumstances are common in many places of the world, once a species has been observed to invade various regions, there is a high probability for the species to become invasive elsewhere (Reichard & Hamilton 1997, Wilson 2004).

### **1.1.3 Why the problem of invasive alien species requires an urgent response?**

Invasive non-native plants are the second most significant threat to biodiversity after habitat destruction, (Environment Agency 2000). Damages caused by species invasions are global and the cost is enormous, in both environmental and economic terms (Pimentel 2002, Lezcano-Caceres & Gerold 2009). Invasive species can transform the structure and species composition of plant communities by repressing or excluding native species, either directly by out-competing them for resources or indirectly by changing the way nutrients are cycled through the system (GIPS 2000, Lowe *et al.* 2000, Spedding 2006).

It is well recognized that there is a global increase in the dominance of the world by a relatively few invasive species, which threaten to create a relatively homogeneous world rather than one characterised by great biological diversity and local distinctiveness (Rejmanek 2000, Rejmanek & Pitcairn 2002). Numerous species, including perhaps as many as 10% of the world's 300,000 vascular plants, have the potential to invade habitats where they are not native (GIPS 2000, Rejmanek 2000, Mack *et al.* 2000 Rejmanek & Pitcairn 2002).

Invasive species can cause the extinction of hundreds of local species by means of out-competing, predating, parasiting and being pathogens for them (Mooney & Drake 1989; Reichard & Hamilton 1997, Munyaradzi & Mohamed-Katerere 2003, Pyšek *et al.* 2004). Invasive alien's species combined with variations in inter-annual rainfall, temperature, human population density, population mobility and pesticide all contribute to one of the most profound affects of invasive species: the threat to human health (McNeely *et al.* 2001). The impacts of invasive alien species are immense, insidious, and often irreversible (GISP 2000, Shine & Gündling 2000).

This research looks at the invasive plant *A. altissima* (Miller) Swingle (Simaroubaceae) and its ecological and economical impacts on the Federal State Hesse, Germany, because *A. altissima* has been shown to cause damage to sewers, foundations, sidewalks, roadways, and power lines in urban areas. *A. altissima* grows in dense stands which displaces native plants however, despite this; there is no information about extinction of other plants due to *A. altissima*'s introduction. Additionally, it is known to produce

chemicals which may kill other plants or prevent plants from growing. *A. altissima* is also known to be poisonous if ingested to animals and small children (Hu 1979, Bluhm *et al.* 1981, Burch & Zedaker 2003).

## **1.2 Description of *Ailanthus altissima***

The genus *Ailanthus* (Simaroubaceae, Quassia family) is native to India, eastern China, Thailand, Malaysia, Borneo, the Philippines, Sumatra, Java, Indonesia, Taiwan, the Solomon Islands, New Guinea and Northern Australia (Nooteboom 1962). The name of the genus is a direct translation from the Indonesian name ailanto. *Ailanthus altissima* (Mill.) Swingle is native to Eastern China. It is a common, naturalized and invasive species found in disturbed areas of North America and Europe, particularly metropolitan areas (Nooteboom 1962).

*Ailanthus altissima* is a deciduous species, which grows rapidly to heights up to 25m, with trunks of up to 1m diameter (sometimes 1,5m diameter). One very common name for the species is “Tree of Heaven”. Other common names are: “china sumac”, “copal”, “tree”, “stink tree”, “ghetto palm”, “ailante”, “ailanthus”, “ailanto”, “ailanthus”, “albero del paradise”, “árbol del cielo”, “a-tree-grows-in-Brooklyn”, “Chinese tree-of-heaven”, “falso zumaque”, “gotterbaum”, “gudstrad”, “heavenwood”, “hemelboom”, “paradise tree”, “piede di cavallo” and “stinking chun” (Hu 1979, Kowarik & Säumel 2007).

### 1.2.1 General botanical characteristics

*Ailanthus altissima* is an early successional species, with limited ability to compete in areas where mature trees produce shadow. However, it can take over forest ecosystems disturbed by natural and anthropogenic alterations (Rabe & Bassuk 1984, Pan & Bassuk 1985, Graves & *et al.* 1989, Miller 1990, Facelli & Pickett 1991, Lodge 1993, Kowarik 1995, Knapp & Canham 2000).

By knowing the botanical characteristics of *A. altissima* it is possible to identify it in the field and begin to formulate a plan to control its population growth (Table 1). *Ailanthus* has alternately arranged compound leaves typically measuring 31 to 91cm in total length with 11 to 25 individual leaflets, heart-shaped leaf scars, and emits an unpleasant smell when the leaves are crushed; making it commonly known as the “stink tree” (Hu 1979, Fig.2 ). Twigs from the plant are smooth to fuzzy and have large shield-shaped leaf scars after the leaves drop. The bark of the trunk is smooth and green, often resembling a cantaloupe when young, eventually turning gray with time. The inflorescence is clusters of yellow-green flowers. In Europe they bloom in late spring to early summer (Fig. 2). Juvenile individuals of *A. altissima* first grow as a single, unbranched stems. When cut back, multiple stems emerge from the ground, eventually resulting in an *A. altissima* mono-cultural thicket. Individual stems can grow 2.44 m in one year and ultimately up to 3.05 m heights. This relatively rapid growth provides the species with a competitive advantage in respect to other plants and also explains why it became an



invasive plant. *Ailanthus altissima* tolerates drought well but does not thrive in areas commonly flooded (Miller 1990).

Table 1 General characteristics that make *Ailanthus altissima* a successful invasive species and conditions that should have the habitat they colonize.

Characteristics <i>Ailanthus altissima</i>	Characteristics of the areas it invades in Europa
<i>Ailanthus</i> is a successional pioneer species , fast grow in open, highly illuminated areas. High versatility and adaptation capacity.	Abundant open, highly illuminated areas native grow is slower.  Occupied extremely wide variety of places to establish itself, (from urban areas to reclaimed surface mined lands).
Successful reproduction with thousand seeds per individual. Easy dispersal wind dispersed seeds.	Native plants don't produce many seeds. Abundant possibilities of dispersion, cars, train, and wind, accidentally carried.
Prolific root or stump sprouting.	Sites suitable for spreading by sprouting after harvest disturbance.
Allelopathic effects on over 35 species of hardwoods and 34 species of conifers have been demonstrated for water extracts of <i>Ailanthus</i> leaves.	
Resistant to insect predation.	New habitat has no predator or natural controls for a new specie.
Resistant to extreme temperature changes.	Native are not resistant to extreme temperature changes.

### 1.2.2 Flowering and Fruiting

The flowers bloom from mid-April to July, from south to north, depending on the latitude. Towards the spring, pollination fall giving place to fruiting. Flower morphology is very variable and some plants have been observed to have perfect flowers, (type of flower that has both pistillate (female) and staminate (male) parts Feret 1973). The flowers are arranged in large panicles at the ends of new shoots (Fig. 2 a, b). As a dioecious species, it bears male and female flowers on different trees, with male trees producing three to four times more staminate flowers than the number of flowers that female trees usually produce (Hu 1979). Staminate flowers are more conspicuous than

pistillate ones (Fig 1). Such staminate flowers produce a disagreeable odour that attracts numerous insects (Hu 1979). The foul odour makes male trees less favoured for ornamental plantings in cities but –in spite of this, the availability of male trees is enough to supply pollen for female individuals otherwise the species would not produce enough seeds to invade vast areas of Europe. Female trees produce pistillate flowers and fruits.



Figure 1 *Ailanthus altissima* staminate flowers

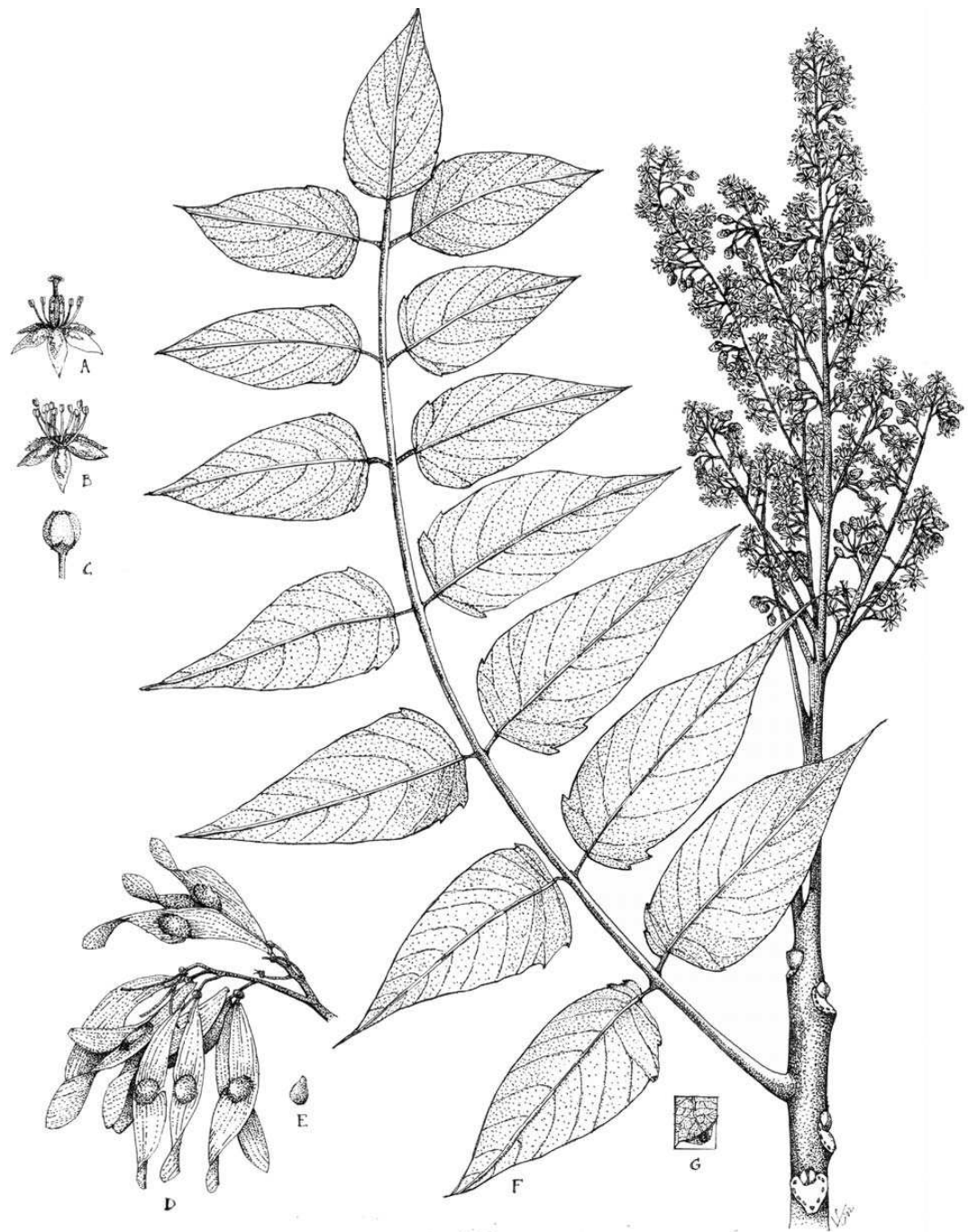


Figure 2 Illustration of *Ailanthus altissima*.

A) pistillate flower, B) staminate flower, C) unopened flower bud, D) samaras, E) individual seed, F) leaflet, and G) gland underneath leaflet (illustration from Call 2002).

### 1.2.3 Seed Production and Dissemination

The fruits are 2-5 cm brown samaras (winged fruits with one single seed each) with the seed in the centre of a thin, oblong wing, well adapted for wind dispersal (Fig.1). A small tree that is 30.48 cm in diameter can produce a million seeds in one year (Illick & Brouse 1926); in fact one kilogram of seeds holds between 27,000 - 33,000 seeds. Such an abundant amount of winged propagules spreads quickly in wind currents found in open areas contributing to the explanation as to why the species became invasive.

The clusters of seeds mature from September to October in the northern hemisphere. The ripe samaras are greenish yellow or reddish brown (Fig. 3). The seed usually persists on the female tree through the winter, characterizing their appearance, but can be dispersed any time from October to the following spring. Trees that are 12 to 20 years old show the most abundant seed production (from 300000 -1000000 seeds/tree, Bory & Clair-Maczulajtys 1980).



Figure 3 Greenish yellow and reddish brown ripe samaras of *Ailanthus altissima*.



#### 1.2.4 Germination, Seedling development and asexual reproduction

Seeds can be sown immediately upon ripening (Sheat 1948), implying that the species has a fast response and a favourable germination. In nurseries, seeds are usually sown in spring and seedlings transplanted early in the following spring. This implies that the plant takes advantage of the summer season to grow (Kowarik & Säumel 2007).

Germination is epigeal (growing on or close to the ground), implying that the plant may start growing quickly on surfaces not covered by other plants; this also explains why *A. altissima* proliferates quickly on asphalt or open soil often found in urban areas (Fig 4). Seeds need to be spread out and to air-dry (Miller 1990, Hoshovsky 1988).



Figure 4 *Ailanthus altissima* seedlings are growing on gravel in urban environment.

Germination sometimes is poor (McMillan-Browse 1985), averaging about 56% (Gordon & Rowe s/f.) One kilo of seeds will normally produce about of 6,500 new seedlings (Duke 1983). Seeds germinate best when treated with a short cold stratification of 8 weeks (McMillan-Browse 1985, Dirr & Heuser 1987). Germination after cold stratification averages 65 to 85 percent (Goor & Barney 1968, Schopmeyer 1974). The recommended cold stratification is 50 °C in moist sand for 60 days.

Vigorous seedlings can grow as fast as 1-2 m during their first year of life (Adamik & Brauns 1957, Hu 1979). The Average survival of eleven different plantings in Indiana strip mines was 74 percent after the first growing season and then decreased to 58 percent after the first winter (DenUyl 1962). Winter weather damages plants and mortality is frequently reported for this species, causing dieback, but re-sprouting does occur (Adamik & Brauns 1957, Goor & Barney 1968, Selenin 1976). Rapid establishment and quick growth during the first year growth (Adamik & Brauns 1957), even under harsh conditions, makes this plant a successful early colonizer especially on disturbed sites (Knapp & Canham 2000, Miller 1990).

*Ailanthus* also reproduces vegetatively via root sprouts (Miller 1990). In an experiment, root suckers emerged from 65.8% of buried root fragments with a length of 22 cm (Singh *et al.* 1992). Even fragments as small as 1 cm in length and a few millimeters in width can produce root suckers (Inverso & Bellani 1991). Seedlings less than 1 year old will respond to cutting with a

remarkably early development of stump shoots and suckers, and will increase in number when subjected to one to three successive cuts within 60 days. Ninety days after each cut, seedlings showed on average 1.5, 4.2 and 13.5 adventitious shoots. Most of these were stump sprouts (Bory *et al.* 1991, Kowarik & Säumel 2007).

### 1.3 Current geographic distribution and habitat requirements

The fossil records indicate that *Ailanthus* experienced a Holarctic distribution through the Tertiary. The distinctive winged fruits of this genus have been described on the basis of impression fossils from numerous sites in western North America, Europe and Asia (Tanai & Suzuki 1963, Tralau 1963, Manchester 1999, Hably 2001).

Since the introduction of *A. altissima* from China in 1751, it has spread over all temperate climates (Fig. 5).

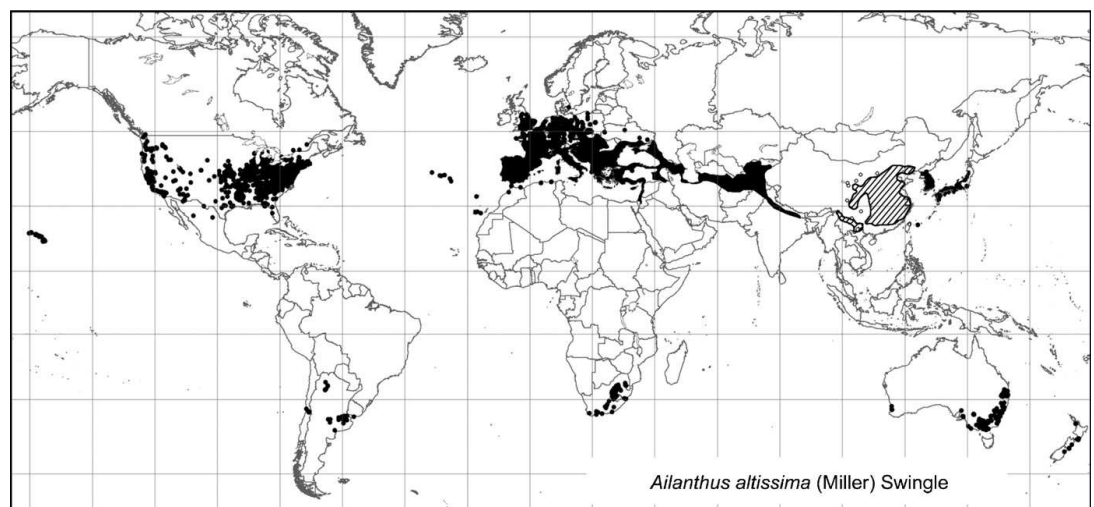


Figure 5 Geographical distribution of *Ailanthus altissima*  
Differentiation of the native Chinese range (hatched; including possible early range expansions within China), and of the secondary world-wide distribution (black) resulting from the range expansion since the introduction of *Ailanthus* to Europe in

the 1740s. Distribution data compiled and mapped by E. J. Jäger & E. Welk, AG Chorology, (©Institute for Biology Halle/Saale).

The altitudinal range of the species is between 0-2000 m.a.s.l., with temperatures ranging from 10-20 °C and mean annual rainfalls from 300-2500 mm.

The plant tolerates extreme soil conditions such as acidic soils with low concentrations of soluble salts and phosphorus. Because of this, *A. altissima* has been used to restore vegetation around mines (Plass 1975). This “accidental experiment” on the tolerance of *A. altissima* to extreme soil conditions also helps to explain why the species was able to settle and become invasive in many industrialized countries. Moreover, the species also colonizes on rich alluvial soils, well-drained to swampy, limestone outcroppings, sterile soils, bottomland coves, and occasionally clay soils or compact clay (Feret 1985, Agro Forestry Tree Database <http://www.worldagroforestrycentre.org/Sea/Products/AFDbases/AF/asp/SpeciesInfo.asp?SpID=1786>) implying the capability of *A. altissima* to settle in favourable areas; for example, when migrating from areas with poor soil conditions to those with good conditions. This species is one of the best adapted adventives within ecological complexes under such conditions as pollution (Jovanović *et al.* 1998, Nestorović & Jovanović 2003) and is even able to grow around springs, and up and out of concrete. Thus, *A. altissima* is one of the most distributed broadleaved tree species in urban biotopes throughout the Eurasian continent.



In addition to the above described wide ecological niche of *A. altissima*, the species produces ailanthone, a compound able to suppress the growth of other plants and eventually kill other plant species (a so-called allelopathic compound, Heisey 1990, 1996; Lawrence *et al.* 1991). This contributes to the formation of dense, monotypic stands of *A. altissima* in invaded areas (Mergen 1959) which would otherwise be occupied by native species. It helps to explain why *A. altissima* occurs in 42 states of the U.S (Swearingen *et al.* 2002). It also explains its exceptionally common presence in urban areas, especially along highways and other roads.

In summary, *A. altissima* is able to grow and proliferate on a broad range of natural and anthropogenically disturbed habitats, as cities. Thus, *A. altissima* is associated primarily with urban environments (Huebner 2003), but it has also been found in secondary and old forests in New York (Knapp & Canham 2000) and West Virginia (Kowarik 1995), affirming it has the potential to become a major invasive tree due to its ability of invasion to be facilitated by various transport corridors.

### **1.3.1 Urban and transportation corridors as pathways of expansion of *Ailanthus altissima* populations**

*Ailanthus altissima* has gained attention for its taking over highway borders around cities (Fig. 6). While outside of cities, *A. altissima* colonizes mostly within transportation corridors, and among these road and railroad verges and medians of motorways (e.g. Adolphi 1995 for the Rhineland). This is

consistent with the winged-propagules of the species (Fig.6) which is capable to blow with the wind and use air currents produced by cars. Mainly starting from roadside verges, *A. altissima* can invade borders of agricultural fields, meadows, and old fields (Kowarik 1983, Facelli & Pickett 1991, Huebner 2003).



Figure 6 *Ailanthus altissima* is becoming a big problem especially alongside of highways and open areas with high illumination.

In southern France, the majority of *A. altissima*-populations within the rural landscapes grew along side of roads, and from there also encroached upon agricultural fields and near-natural shrub communities by colonel growth (Kowarik 1983, Table 2). *Ailanthus* is common on Mediterranean islands (Lloret *et al.* 2004, Vila *et al.* 2006), and on Crete, its distribution is linked to the main transport network of major roads (Hulme 2004). Studies from eastern North America show similar distribution patterns.

Table 2 Range of habitats colonized by *Ailanthus altissima* outside of settlements in the Département Gard, southern France (adapted from Kowarik 1983), and West Virginia, United States (adapted from Huebner 2003, the percentage are based on all habitat types noted in a land use map of West Virginia 2000).

Southern France	%	West Virginia	%
Roadsides	57.7	Roadsides	43.1
From roadsides			
Encroaching into agricultural fields and vineyards	16.7	Railroads	11.8
Encroaching into near-natural evergreen shrub communities	19.2	Trails	5.9
Water courses	5.1	Water courses	17.6
Forests	1.3	Forests	5.9
		Other	15.7

From: Biological flora of central Europa: *Ailanthus altissima* (Mill.) Swingle, Kowarik & Säumel 2007.

In south-western Virginia, North Carolina and western Himalayas, *A. altissima* colonizes primarily along major highways, but it is even more prevalent along side of railroad rights-of-way (Singh *et al.* 1992, Burch & Zedaker 2003, Merriam 2003). It also colonizes many other types of linear habitats, such as railroad verges and stream banks, forest edges and skid trails in forests (Call & Nilsen 2003, Huebner 2003, McDonald & Urban 2006, Table 2). In South America (Santiago de Chile, Buenos Aires and Mendoza Provinces) *Ailanthus* grows in cities, on abandoned lands and along railway embankments, road verges, small rivers and creeks.

#### **1.4 Uses of *Ailanthus altissima*, medicinal properties and Toxicity as potential causes of its invasiveness**

As described in 1.1., one of the reasons why humans move potentially invasive plants from one region to another is due to the potential use the plants have for humans. *A. altissima* was used as an ornamental plant, for

reforestation, afforestation, firewood, and even as potential fodder for domestic animals (not used by it toxicity); it was also used to cure dysentery (Hu 1979, James 1983, Feret 1985). *A. altissima* was used as a source of pollen and nectar for honey producing bees (Melville 1944) and was considered to be a high-quality candidate for industrial production of pulpwood (Illick & Brouse 1926). It has also been cultivated and utilized for erosion control around the Black Sea and in the mountains of Morocco (Pieglar 1993, Call 2002). Like most herbaceous and woody weeds, *A. altissima* has been recently suggested as a candidate for developing bio energy.

*Ailanthus altissima* is less used in western herbal medicine; though it is herbal use is popular in Asia. The bark is the most commonly used part; however various parts of the plants can be used as well. The bark contains a glycoside that is not fully researched and therefore should be used with caution (Chiej 1984). The root and stem bark contains a bitter substance and is used as antispasmodic, astringent, cardiac depressant, diuretic, emetic, febrifuge, rubefacient and vermifuge for worms other than round and earthworms (Grieve 1984, Usher 1974, Duke 1983, Yeung 1985, Stuart s/f, Duke & Ayensu 1985, Bown 1995). Since the bark easily induces vomiting, it needs to be used under the supervision of a qualified practitioner (Bown 1995). A nauseatingly bitter tree, it is used internally to treat malaria and fevers; it also slows down the heart rate and relaxes spasms (Bown 1995). In China, the bark is a popular remedy for dysentery and other complaints of the bowels (Grieve 1984). In a clinical trial, 81 out of 82 patients were cured of dysentery when treated with this tree (Chevallier 1996). A tincture of the root-

bark was used successfully in the treatment of cardiac palpitations, asthma and epilepsy. *A. altissima* is a folk remedy for asthma, cancer, diarrhoea, dysentery, dysmenorrhoea, dysuria, ejaculation (premature), epilepsy, eruption, fever, gonorrhoea, haematochezia, leucorrhoea, malaria, metrorrhagia, sores, spasms, spermatorrhoea, stomachic, tumours of the breast (Duke 1983).

The leaves, bark of the trunk, and roots are used to treat parasitic ulcers, itch, and eruptions (Duke 1983). In Korea, the root bark is used in the treatment of coughs, gastric and intestinal upsets (Duke 1983). The stem bark is emmenagogue (Duke & Ayensu 1985). The leaves are anthelmintic, astringent and deobstruent (Duke & Ayensu 1985). The fruit is used in the treatment of bloody stools and dysentery (Duke & Ayensu 1985, Duke 1983). They have also treated ophthalmic diseases (Duke 1983). Extracts of the plant are bactericidal (Duke & Ayensu 1985). The tree is used in homeopathic remedies for cancer (Duke 1983). A resin extracted from the roots and leaves is a revulsive or vesicant (Duke 1983).

As common with many medicinal plants, *A. altissima* has toxic properties related to the intense, disagreeable smell and flavour of the leaves and its ability to cause headache, nausea, rhinitis and conjunctivitis; also the pollen can cause "hay fever" (Mitchell & Rook 1979, Jin *et al.* 2006). Leaves are toxic to domestic animals (Perry 1980). The toxicity levels of the leaves are higher during the early growth season and remain high at least until October (Voigt & Mergen 1962) so gardeners cutting trees down may suffer rashes. This disadvantage for humans however, is small, compared to the many uses

the species demonstrated or otherwise humans would not have contributed to its transportation, nursery and expansion of *A. altissima*-populations around the world to the extent of it to become invasive; even producing millionaire economic losses.

### **1.5 Economical Problems, invasion prevention and control**

*Ailanthus altissima* can cause serious damages to foundations, sidewalks, roadways, and power lines in urban areas when roots uplift these infrastructures (Lezcano-Caceres & Gerold 2009). Another economic damage occurs when the plant kills other plants species in agricultural fields and natural habitats by means of its allelopathic substances. If ingested, it can poison economically important animals and even children (Perry 1980, <http://www.peconicestuary.org/InvAilanthus.html>, consulted Nov 2007). Because of these reasons, *A. altissima* is considered a weed in Europe. Invasive plants produced losses of more than 167 million Euros in Germany (UFZ 2002) therefore millions of Euros are invested to control their populations. In fact, the control of *A. altissima* costs up to 5 million Euros to the public and private sectors in Germany (Lezcano-Caceres & Gerold 2009). Hence the importance of establishing controls to prevent its spread, and is in part, the aim of this dissertation.

The methods of weed management are commonly categorized under the following five categories: physical, thermal, chemical, biological, and

managerial (Watson 1977, Hoshovsky 1986, 1995). All of them are used against *A. altissima*-populations.

Some common physical controls are:

- **Hand-pulling** of the seedlings and small saplings: The plants must be pulled out the ground as soon as they are large enough to grasp, especially before they produce seeds. The best time is after a rain because water loosens the soil surrounding the root making it easier to pull. It is critical to remove whole root system or the plant will sprout again.
- **Cutting of large individuals**: Trees should be cut at ground level with a power or manual saw. This method is most effective when the tree has begun to flower, because the selection of only flowering branches prevents seed production more efficiently. Sprouts may grow after a cutting so repeated cutting is required.
- **Girdling of very large individuals**: A cut through the bark encircling the base of the tree should be made with an axe, approximately 15 cm off the ground. The cut should be made well into the group of live, growing tissues botanically known as *cambium layer* -which is under the bark of the tree, and be extended into the woody part of the tree for avoiding the regeneration of the cambium. This method works by killing the top of the tree. As with the cutting method, sprouting may occur, and follow-up treatments must be made for several years until the roots exhaust all nutrient-reserves thereby stopping to supply energy for the sprouting of new branches and leaves (Mauseth 2008).

**Biological control** of *Ailanthus* has not been addressed to any extent beyond the anecdotal stage. No susceptibility of *Ailanthus* to parasites was found or noticed in Austrian nurseries (Adamik & Brauns 1957). The fungus known as zonate leafspot (*Cristulariella pyramidalis*) causes defoliation of *Ailanthus* in Florida (French 1972). In India, *Atteva fabricella* is considered an *Ailanthus* defoliator (Misra 1978) and in Italy seedlings, weakened by cold, were weakly parasitized by the fungus *Placosphaeria* spp. (Magnani 1975). The potential biological “toolbox” to control *A. altissima* may consider other fungal pathogens, (*Verticillium dahliae* and *Fusarium oxysporum*) that have been isolated from dead and dying *A. altissima* trees in New York and in southern and western Virginia (Cech 1998, Skarmoutsos & Skarmoutsou 1998).

## 1.6 Working Hypotheses

The following chapters of this dissertation present a series of studies conducted between the summer of 2005 until the summer of 2008 where the spatial distribution, population ecology, eco-physiology and economic impacts of *A. altissima* were studied in the German Federal State of Hesse. The assumptions of this study were:

1. *Ailanthus altissima* is scattered along the streets and train stations because they work as corridors for the arrival of its seeds as well as



past human-induced introduction. Larger train stations should have more individuals of *A. altissima*.

2. Once in cities, *A. altissima* can grow in a diverse group of urban microhabitats. Including; neighbourhoods should have a higher density of individual plants than those plants found in green areas.
3. *Ailanthus altissima*, as a pre adapted species to urban environments, should not be individuals in forest near cities because other native trees had colonized earlier.
4. *Ailanthus altissima* grows along rural - urban environments and its abundance decreases in rural environments.
5. Cities which have cement infrastructures and if *A. altissima* is an “urban-pre-adapted” plant, then the plant should be able to grow well on gravel. However, this growth should be limited by intraspecific competition when the density of individuals is high and by inter-specific competition if other species (e.g. grasses) are previously present.
6. Physical control techniques are the most expensive compared to other control techniques.

## CHAPTER 2

### 2 General Methodology

#### 2.1 Study Area

The study was conducted in the Federal State of Hesse (Fig. 1) located in central-western Germany. Hesse covers 21,110 km<sup>2</sup> and has more than six million inhabitants. Average temperatures range from 4.9°C (winter) and 12.3°C (summer). Its largest city is Frankfurt am Main (672 667 inhabitant Statistisches portrait 2008), where summers are warm and wet with temperatures varying between 14 - 33.6°C along with frequent rains. Winter is quite chilly with temperatures dropping to -7.6°C. The average precipitation is to 560 mm per year. Elevations range from 0 - 800 m. a. s. l. (DWDW 2007).

Frankfurt is the financial and transportation centre of Germany and the largest financial centre in continental Europe. It is the seat of the European Central Bank, the German Federal Bank, the Frankfurt Stock Exchange and the Frankfurt Trade Fair, as well as several large commercial banks. Frankfurt Airport is one of the world's busiest international airports, Frankfurt Central Station is one of the largest terminal stations in Europe, and the Frankfurter Kreuz (*Autobahn* interchange) is the most heavily used interchange in continental Europe. Frankfurt is the only German city listed as one of ten Alpha world cities with a high concentration of vehicular traffic including millions of cars passing through their streets and highways, which

facilitate the dispersion of plant species producing winged seeds such as *A. altissima* (Beaverstock *et al.*1999).

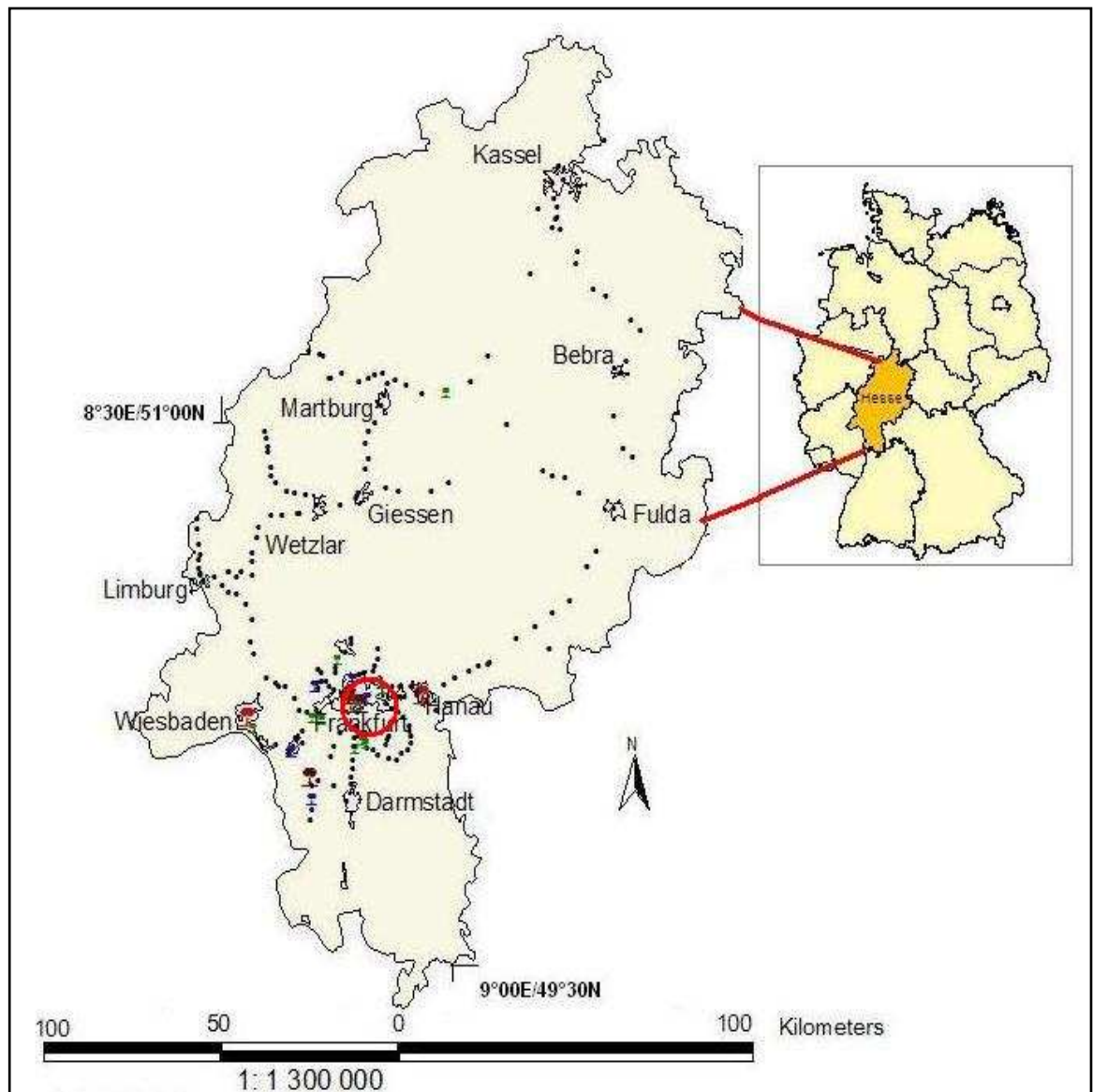


Figure 1 Map of study area (the federal state of Hesse, Germany). The figure shows the visited train stations and the area where the plots for the urban-rural study were established.

The complete study was conducted from June 2005 until March 2008 and includes four parts detailed as follow:

## **2.2 Distribution of *Ailanthus altissima* on the Hesse's Train Stations and across an Urban gradient**

### **2.2.1 Train stations**

In order to test if *A. altissima* abundance and population structure depends on the size of train stations, I surveyed *A. altissima* individuals in train stations of different sizes during the summers of 2005 and 2006. After ensuring that the largest train station (Frankfurt) was going to be part of the study, I randomly selected 234 railway stations from the 425 stations found in Hesse (55% of the total train station in Hesse). The population of *A. altissima* was divided into 3 size categories: (1) seedlings and small saplings (seedlings and small saplings being, 1cm height - 1cm diameter at 1.3 m above ground, dbh), (2) large saplings and juveniles (1cm dbh - 10cm dbh) and (3) trees (> 10cm dbh). These individuals were located along a 250 m-length transect on both sides of each boarding platform of each train station (Fig. 2). The size of each station was also estimated, the number of railways was counted to determine the area, all this data was confirmed in labour with google map and converted in hectarea and each station was positioned *in situ* using a Global Positioning System device -GPS (Garmin e-Trex 12X) in order to develop a distribution map. All individuals of *A. altissima* were counted and the numbers of individuals were standardized into densities (individuals per hectare).



Figure 2 Illustration of the transect in each station studied.

### 2.2.2 Urbanity gradient

In order to test if *A. altissima* grows more often in urban- vs non-urban areas, I surveyed its individuals during the summer of 2005 and the spring of 2007 in the city of Frankfurt am Main and the surrounding villages (Offenbach, Oberursel, Königstein) and in the neighbouring Taunus Forest. I chose 25 plots 18 hectares each (300 × 600-m) along a transect representing an urban gradient ranging from almost zero inhabitants (forest-covered area) to more than 4000 inhabitants/km<sup>2</sup> covering a “grey, cement-built area” (Frankfurt). In each plot, I counted all individuals of *A. altissima* and classified them into the above described size categories: (1) seedlings and saplings (seedlings and small saplings, 1cm height - 1cm diameter at 1.3 m above ground, dbh), (2) large saplings and juveniles (1 cm dbh - 10 cm dbh) and (3) trees (> 10cm dbh).

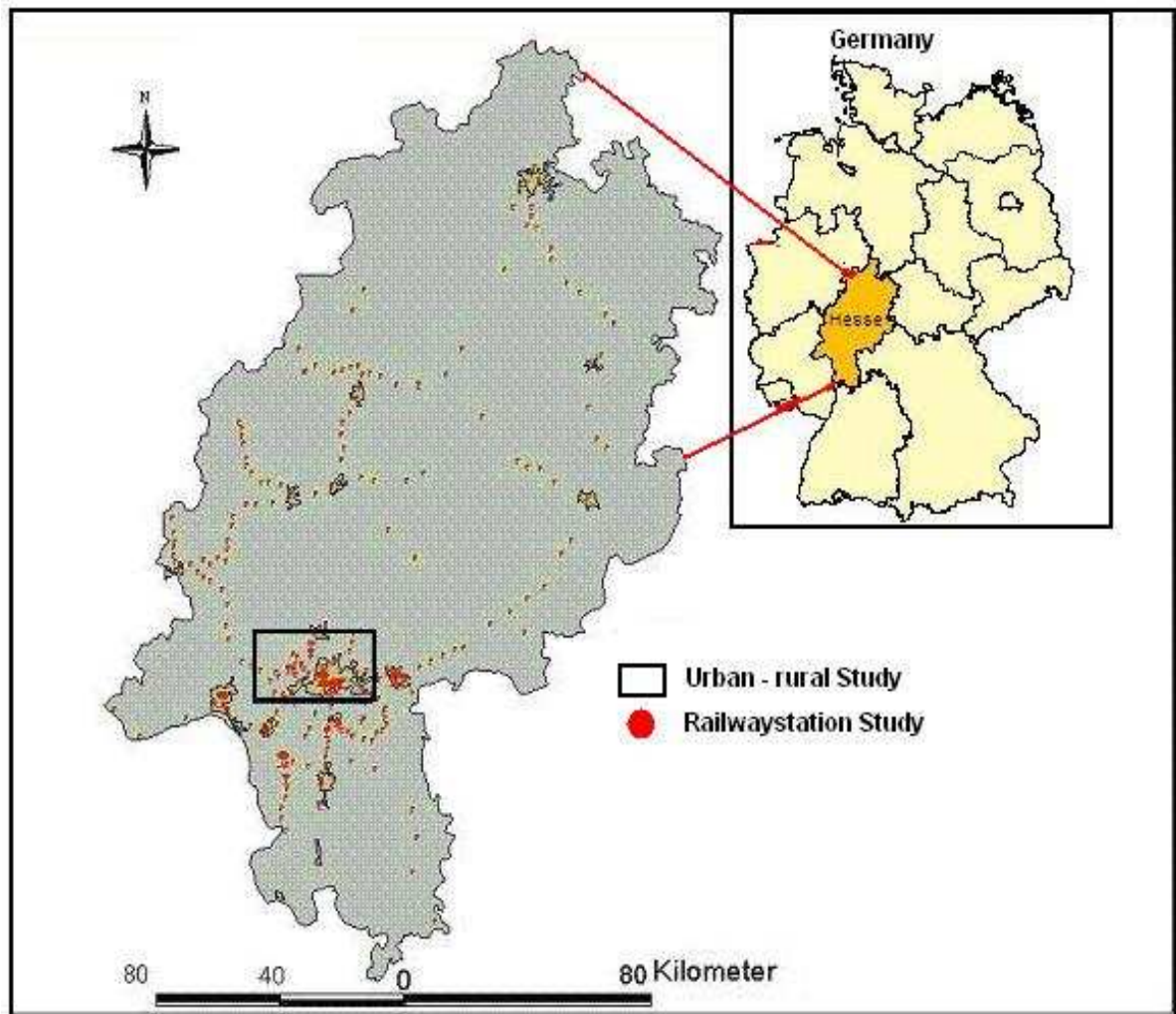


Figure 3 Location of the research plots in Hesse, Germany. Research area include from cities (gray, cement areas) to forest area in Taunus.

We used human population density as an indicator of urban intensity, where higher numbers of human inhabitants were present represents higher urban intensities. We used *A. altissima* density (individuals per hectare) as the response variable for all analyses (see Chapter 2).

### **2.3 *Ailanthus altissima* germination and growth under different kind of substrate and seed densities.**

In order to determine if the germination and growth of *A. altissima* is inhibited by grasses and how germination changes according to the substrate and



densities of *A. altissima* seeds and seedlings, I investigated the germination and growth of *A. altissima* in 27 plots (1m<sup>2</sup> each) in the Botanical Gardens of the Johann Wolfgang Goethe University during the summer of 2006. Seeds were germinated and grown on three different substrates: soil + grass, bare soil and gravel, seeds were also planted in the following densities: 100, 150 and 200 seeds/m<sup>2</sup> (Fig. 4). The seeds were sown in April and were maintained for three months to study the subject at natural conditions. After this period, plants were harvested manually and data of wet weight was collected, after two weeks in a drying oven they were again measured to obtain a dry weight (see Chapter 3).



Figure 4 Example of a plot for studying the germination and growth of seedlings and saplings of *Ailanthus altissima*.

Research conducted at the Botanical Gardens of the Johann Wolfgang Goethe University of Frankfurt. Three kinds of substrate were used: bare soil, gravel and soil + grass, as well as three different seed-densities: 100, 150 and 200 seeds/m<sup>2</sup>.

## 2.4 Population Dynamics of *Ailanthus altissima*

In order to consider if the populations of *A. altissima* can grow faster in an urban area compared to a less urban one, as well as what individual size classes were more necessary to control (e.g. seedlings vs adults), I surveyed *A. altissima* populations during the summers of 2006 and 2007 in two randomly selected plots of 300 x 600m and used the data to estimate population changes by means of Leslie Matrixes. The plots were located in the city centre and outskirts of the centre of Frankfurt (Fig.5).

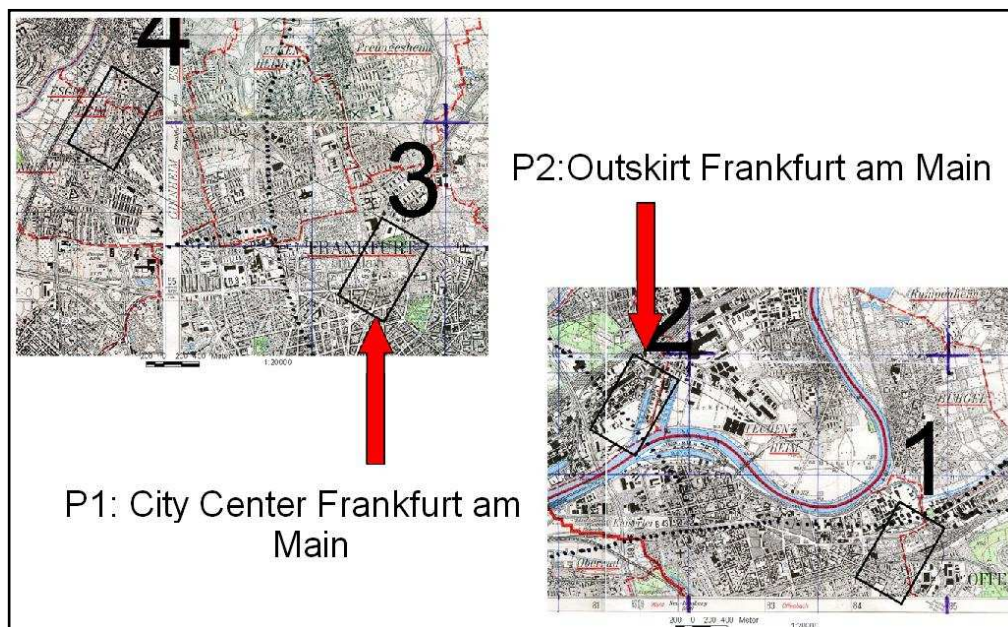


Figure 5 Location of the dynamic population of *Ailanthus altissima* research plots in Hesse, Germany. Research area included one plot in Frankfurt Centre P1 and one in the outskirts of Frankfurt P2.

A total of 600 individuals were surveyed during two years. Using the former made it possible to determine the recruitment of new individuals which is necessary to determine the potential population dynamics using Leslie Matrixes. In the reproductive season (July to October) flowering individuals were studied and the production of new seeds was estimated. Germination



percentage was also evaluated for two months in 30 small subplots (1 m<sup>2</sup> each). Population of *A. altissima* was divided in five-stage (C<sub>1</sub> to C<sub>5</sub>) of life cycle and their transition probabilities (growth, survival and fertility) in both populations -as represented in Fig. 6, were used for the matrix calculations (see Chapter 4).

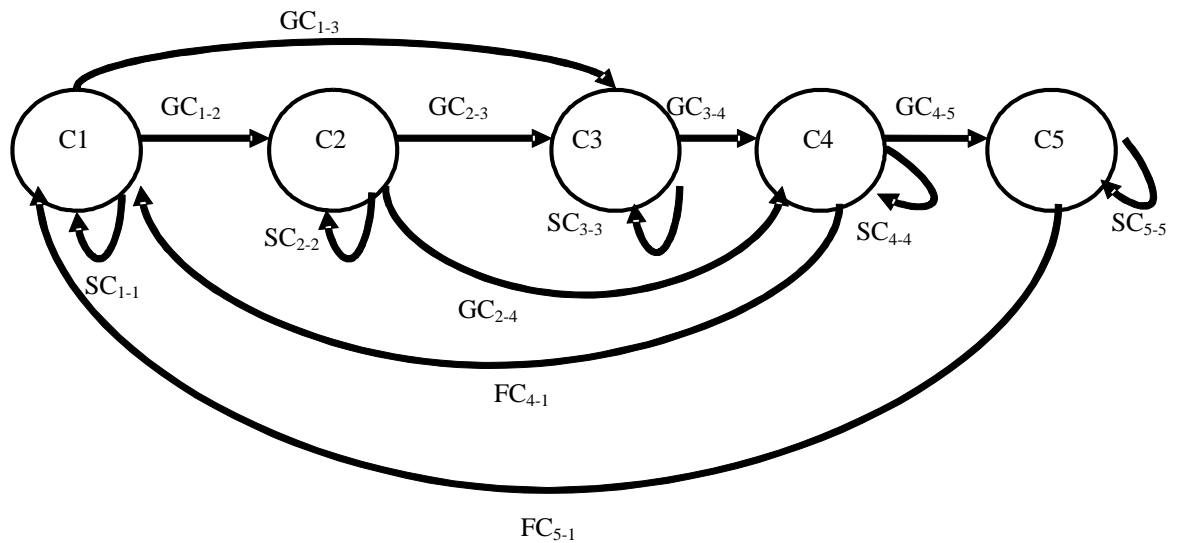


Figure 6 Life-cycle diagrams of *Ailanthus altissima*.

The diagram shows the five developmental-stage classes considered and all possible transitions among them. G = all individuals which grow to the next group; S = all individuals who survive to the next group, F = fertile individuals that are incorporated into the first stage.

## 2.5 Evaluation of the controlling costs of populations of *Ailanthus altissima* in Hesse

In order to determine how expensive it is to control the populations of *A. altissima*, I conducted a series of informal interviews (because of the sensitive information that I required on control methods and costs of investments, sometimes caused anxiety when answering by the survey takers) in 2005 and 2007. In concrete, the interviewed were conducted with

10 top-directors of parks, three top-managers of the German Railway Company (Deutsche Bahn –DB) and two top-officers of the health authorities. They were asked for the management costs, equipments (Fig. 7), salaries and costs for the control of *A. altissima* in the whole state of Hesse. Printed information supplied by DB ([www.db.de/sustainability-report](http://www.db.de/sustainability-report)) and the costs anti-allergic treatment was also consulted (see Chapter 5).



Figure 7 Fisical control (Pruning) used on the control of *Ailanthus altissima* population in Hesse, Germany.

## CHAPTER 3

### ***Ailanthus altissima*, a successful invasive tree species in large train stations and cities in the federal state of Hesse, Germany.**

#### **Summary**

*Ailanthus altissima* is an invasive tree species colonizing open areas and its roots destroy railways, house foundations, and streets and have an allergy producing pollen. Thus, many millions of Euros are annually invested in its control. It is proposed that the more intense level of urbanism of a given area, the more abundant is *A. altissima*. For testing this, we compared the abundances of *A. altissima* across categories of train stations according to their traffic intensity, along an urban-rural gradient of a landscape, and in plots within cities; all these which were located in Hesse, Germany. Major train stations had more individuals of *A. altissima* and the same occurred for larger cities in respect to small cities and forest areas. Within cities, neighbourhoods had more *A. altissima* individuals per hectare than green areas like parks and cemeteries. Non biotic conditions (e.g. changes of temperature) have been proposed to explain the above mentioned pattern. We also stress that trains and cars may act as seed dispersers and that cultural practices like pruning in cemeteries and parks reduce the populations of *A. altissima*. Controlling this invasive species requires coordinating efforts from public and private sectors, including those of a train company and municipalities in order to avoid the exchange of propagules across their installations. Expanding such coordinated strategies to all European countries may save millions of Euros in the near future.

### 3.1 Introduction

*Ailanthus altissima* (Mill.) Swingle, commonly known as tree of heaven, is a pioneer tree native to eastern China, was introduced to Europe through England in 1751 (Nooteboom 1962, Feret & Bryant 1974, Hu 1979, Knapp & Canaham 2000, Han-wool & Chang-Seok 2006, Kowarik & Säumel 2007) and became invasive in Germany and other countries producing millionaire losses of money. For example, just in the Federal State of Hesse, Germany, *A. altissima* produced a loss of five Million euros between 2006 and 2007 (Lezcano - Caceres & Gerold 2009).

Its growth is enhanced by high incidence of light; soil movement favours the germination of its seeds when they fall on bare and well ventilated soil. Roads and railways are well known as corridors for the rapid spread of invasive plants (Tyser & Worley 1992) probably due to cars and trains carrying seeds. *A. altissima* is commonly found near train stations and in cities, seed dispersal is favoured by the movement of cars and trains; all this explains why *A. altissima* is invasive mainly in urban areas (Corbett & Manchester 2004, Huebner 2003).

*Ailanthus altissima* invades places where conditions do not allow other species of plants to grow and proliferate (Call & Nilsen 2005). Their shoot and root sprouts make it a progressing aggressive competitor with respect to the surrounding vegetation (Hoshovsky 1988, Kukk *et al.* 2001).

The female trees produce large quantities of seed (300,000 to one million per year) that are dispersed by wind (Nootebomm 1962, Hoshovsky 1988). The seeds have a high germination rate, between 57-65% (Lezcano-Caceres in prep., Hoshovsky 1988) and developed in a variety of disturbed habitats, along railroad tracks as well as urban and suburban areas. All these characteristics make it difficult to control the *A. altissima* population. Therefore, in most cities it creates many problems because its roots cause damage to building foundations, water channels, and uplifts street pavements and sidewalks (Hoshovsky 1988).

City habitats provide special conditions such as warmer environments, wind protection and allow for easy seeds dispersal due to soil movement. Many studies were carried out considering these special characteristics which seem to favour the dispersion of introduced species, (Whitaker 1967, Stearns & Montag 1974, Shelton 1974, Greller 1975, Brady *et al.* 1979, Kowarik 1990, McDonnell & Pickett 1990, Pouyat & McDonnell 1991, Pouyat *et al.* 1995, Sukopp *et al.* 1995, Blair 1996, Sukopp 1998, Zhu & Carreiro 1999).

In central Germany, floristic researches on urban sprawl pointed out that there is a kind of urban gradient where the introduced plants can adapt and disperse based on warmer microclimate in the cities (Müller 1987, Gutte *et al.* 1987, Kowarik 1992). In this sense, *A. altissima* is a much researched tree; and as a pioneer tree with strong urban character (Wittig 1998).

*Ailanthus altissima* grows and reproduces successfully in dry soils (Adamik & Brauns 1957, but see Bory & Dubroca 1981) and is sensitive to frost,

especially during its early growth years (one or two year old plant) (Adamik & Brauns 1957). Selenin (1976) reported that older individuals of 6 years of age have survived winters of -33 °C with strong winds.

*Ailanthus altissima* tolerates polluted environments with high CO<sub>2</sub> concentrations and its resistance to insects attacks (Shah 1997) which explains its success in highly disturbed habitats such as roadsides. Moreover, the movement of motor vehicles (e.g. cars) facilitates seed dispersal (Kowarik & von der Lippe 2006). If this is so, then high traffic trains sites should also be prone to invasions by *A. altissima*, hence Deutsche Bahn invests 62 million per year to control this and other invasive species.

This study determined the distribution of the species among the railway stations in Hesse. There, two million people move by cars and trains throughout Frankfurt and its surroundings. Indeed, Hesse is a good example of what happens in many big cities in Europe. In addition we consider equally the size and traffic patterns at the station. The data were analyzed to produce distribution maps of *A. altissima* which are necessary to learn how the tree is moving and where it is necessary to present a strong control of the population and to analyze patterns of colonization of *A. altissima*. We also analyze the influence of urbanism on the abundance of *A. altissima* the features considered were: condition (rural or urban) habitat types (four in total: neighbourhood, cemeteries, parks and industrial), human population density and elevation. The information obtained from this study will help to design and develop control management strategies for this species.

## 3.2 Materials and Methods

### 3.2.1 Study area

The study was conducted in the Federal State of Hesse (Fig.1) located in central-western Germany. Hesse covers 21,110 km<sup>2</sup> and has > six million inhabitants. Average temperatures range from 4.9°C (winter) and 12.3 °C (summer), DWD (2007). Elevations range from 0 to 800 m. a. s. l. A type of biological corridor runs through the central region of Hesse to its highlands called "The Hessian Corridor", which has been an important route connecting Frankfurt and Hannover South.

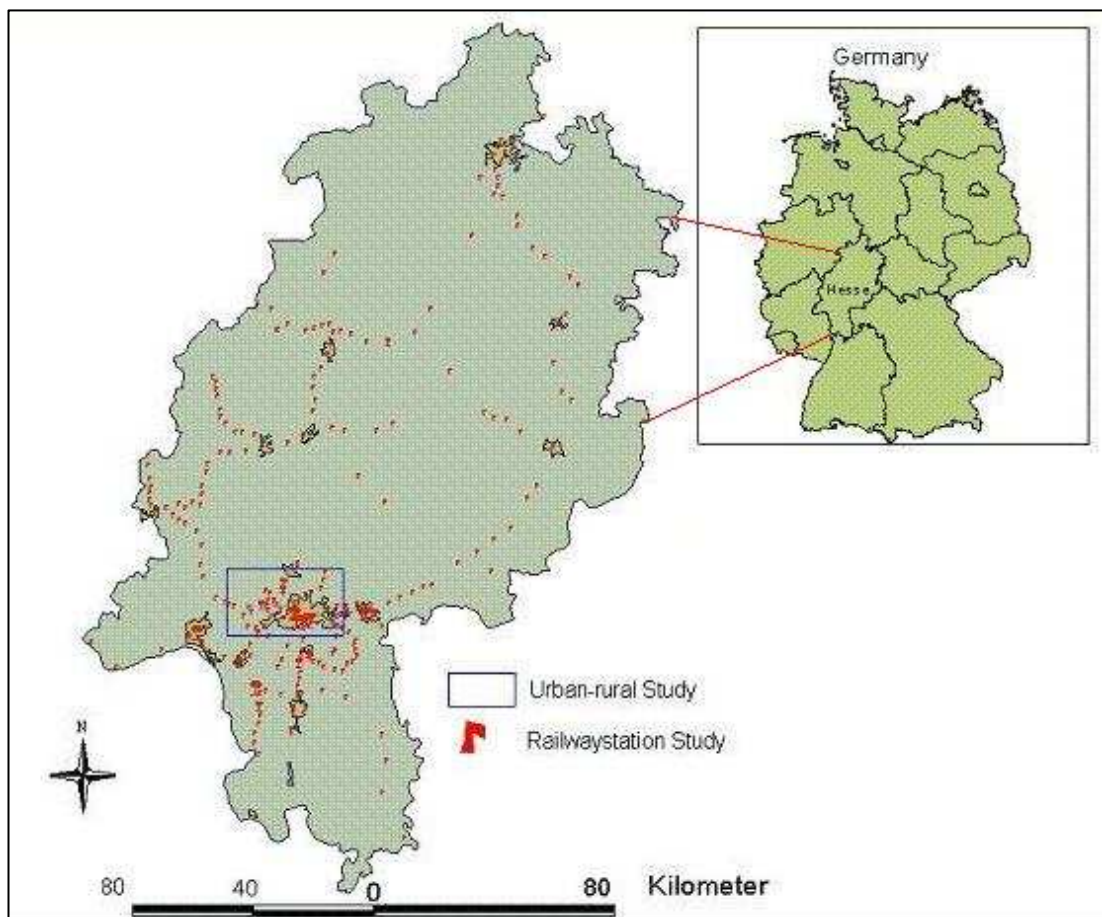


Figure 1 Map of study area with the visited train stations and plots for the urban-rural study in Hesse, Germany.

The map shows the area where the plots to study populations of *Ailanthus altissima* were established.

### 3.2.2 Sampling Design

#### 3.2.2.1 Train Stations

During the summers of 2005 and 2006 we randomly selected 234 railway stations representing 55% of the total number of stations in Hesse (see red points in Fig. 1). During our study period, the German train company maintained 425 active railway stations. The stations were classified into six categories based on the system established by the German train company Deutsche Bahn (2007, [http://www.deutschebahn.com/site/bahn/de/geschaefte/infrastruktur\\_schiene/personenbahnhoefe/bahnhofskategorien/bahnhofs\\_kategorien.html](http://www.deutschebahn.com/site/bahn/de/geschaefte/infrastruktur_schiene/personenbahnhoefe/bahnhofskategorien/bahnhofs_kategorien.html)) as follows: 1= traffic hubs similar to international airports in terms of service. Such train stations are permanently staffed and carry all sorts of railway-related facilities; they usually function also as shopping malls. 2= important junctions of long-distance traffic or stations offering connections to large airports. Inter City and Euro City trains generally stop at these stations. All railway-related services, such as a ticket hall and a service desk, are present at the station and the station is staffed during the usual times of traffic. 3= are regional hubs with possibility of intercity services. These stations will usually feature a station hall where travellers can buy tickets and groceries, but these stations are usually not permanently staffed. 4= highly-frequented local traffic stops and hubs. Inter-city trains usually do not stop there, but they have frequent connections with Regional Express and Regional Bahn trains. Their service level is comparable to a bus station and they offer services to commuters. 5= stations belonging either to small, rural towns or to outlying suburban areas of major cities. Their inventory normally is "vandal-proofed" due to the lower number of



passengers. They normally have Regional Express trains stopping at the station at least every hour. Finally, 6= stations with the lowest passenger numbers and have only the most basic equipment needed; such stations are very similar to bus stops.

The population of *A. altissima* was divided into 3 size categories: (1) seedlings and saplings (seedlings and small saplings, 1 cm height - 1cm diameter at 1.3 m above ground, dbh), (2) large saplings and juveniles (1 cm dbh - 10 cm dbh) and (3) trees (> 10cm dbh). In every train station we established a 250m-length transect on both sides of the boarding platform (Fig. 2), counted the number of individuals of *A. altissima* and standardized it into density (individuals per hectare) of *A. altissima* at the railway was calculated. We also scored the number of existing rail lines at each station. Additionally, the stations (and other studied sites as well) were located in situ using a Global Positioning System device -GPS (Garmin e-Trex 12X) to get accurate data to develop a distribution map.

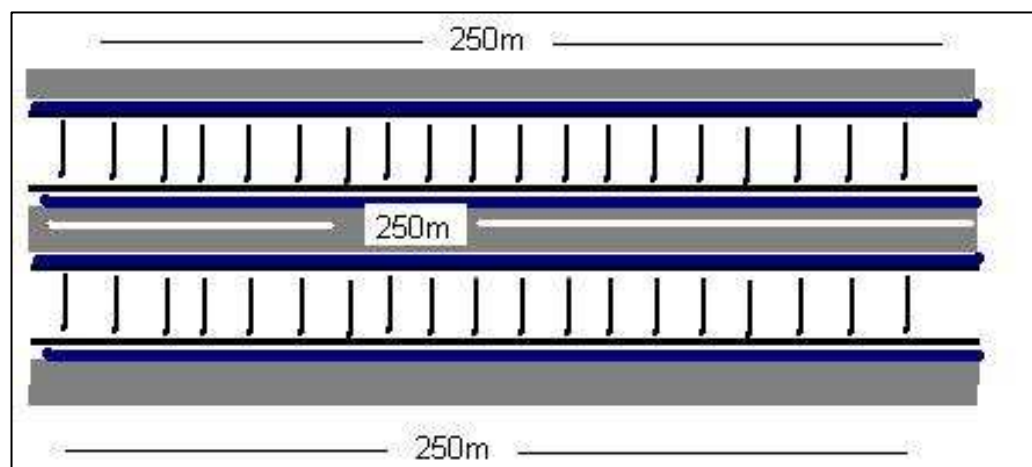


Figure 2 Illustration of the transect in each station studied.

### 3.2.2.2 Urbanity gradient, plots settlement and data collection

The study was conducted in the city of Frankfurt am Main the near villages of Offenbach, Oberursel, Königstein and in the Taunus Forest during the summer of 2005 and the spring of 2007. Temperatures in the area range from 5.4- to 10.7°C, annual rainfalls from 560-to 1 000mm, and altitude from zero-to 870 m. a. s. l. (Deutscher Wetterdienst –DWD 2007, Fig. 3). These climatic and altitudinal variation were not related to our results (data not shown). We settled 25 plots 18 hectares each (300 × 600-m) along a transect representing an urban gradient ranging from almost zero inhabitants-and forest-covered area (Taunus) to more than 4000 inhabitants/km<sup>2</sup> covering a “grey, cement-built area” (Frankfurt, Fig. 3). In each plot, we counted all individuals of *A. altissima*. The first plot was randomly selected without a compass and the rest were located systematically based on a range of 3.0 to 3.5 km from the nearest plot going to the Northwest. We used geo e-Trex Garmin Handheld GPS Navigator 12X to delineate each plot and determine the altitude. Although the GPS system has been designed to be as accurate as possible, there are still errors. Taken together, these errors can cause a deviation of ± 50 to 100 meters of the GPS receiver position). Of the 25 plots, 16 were in urban areas and nine plots in rural areas (Fig. 3)

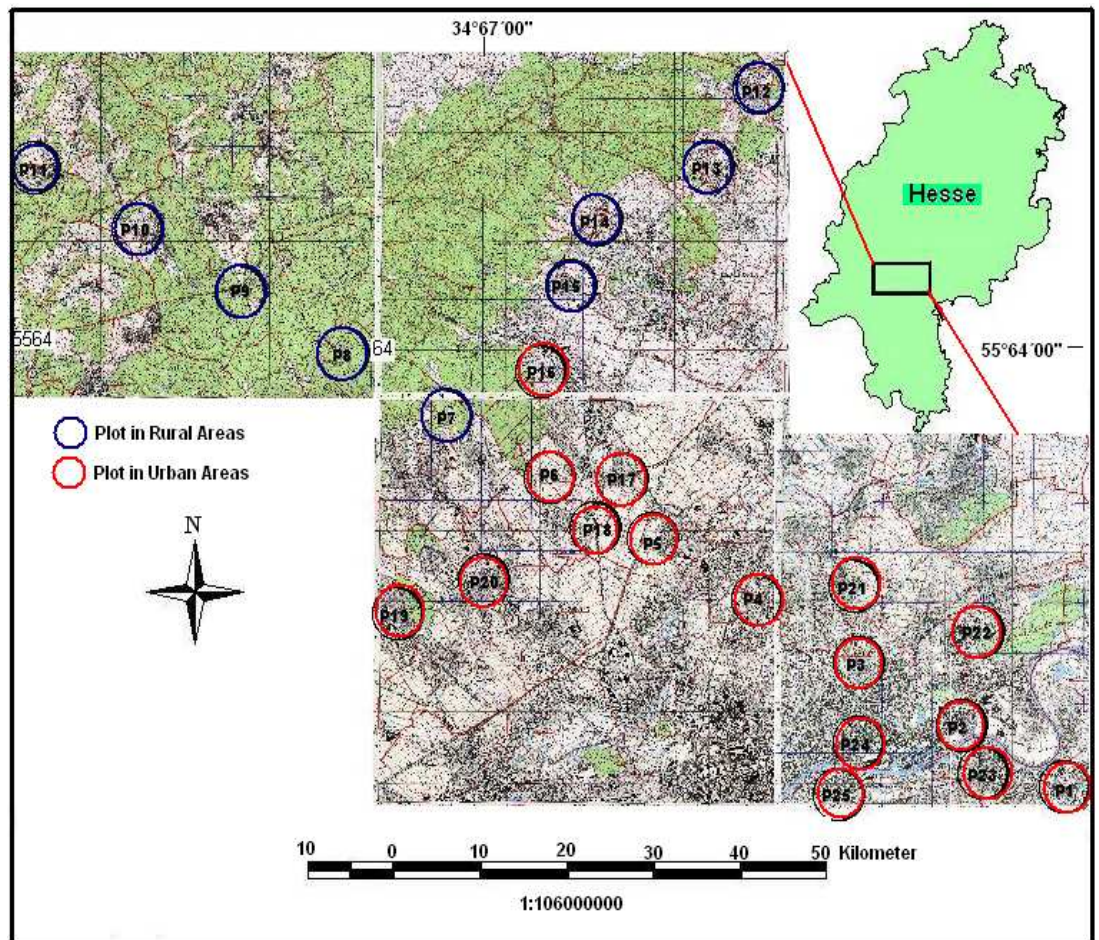


Figure 3 Location of twenty five 18-hectare plots representing an urban-to-rural gradient where *Ailanthus altissima* population was studied in Hesse, Germany. Sites are: Offenbach Ost= P1, Ostend (Hafen)= P2, Frankfurt City Nordend East= P3, Eschersheim= P4, Niederursel= P5, Stierstadt= P6, Weißen Berg= P7 Altkönig= P8, Rotes Kreuz Kleiner Feldberg= P9, Oberems= P10, Niederems= P11, Köppern= P12, Friedrichsdorf= P13, Dornholzhausen= P14, Oberstedten= P15, Oberursel= P16, Weißkirchen= P17, Bad Homburg= P18, Bad Soden= P19, Neuhochstadt-Sulzbach= P20, Preungesheim= P21, Enkheim= P22 , Kaiserlei= P23, Zoo= P24, Sachsenhausen SüdBhf= P25. Of all these 25 plots, 16 were in urban areas and 9 plots in rural areas

We used human population density as an indicator of urban intensity, where higher human population density means greater urban intensity. Thus, for each of the 25 plots we estimated human population density as follows: (a) determining in what district each plot was located and borrowing the number of inhabitants of the district as registered at the last National Census for the

district (Comptroller General of the Republic 2006), (b) determining how many square kilometre of each plot were effectively populated (e.g. outside cemeteries or parks) and (d) intrapolating the number of inhabitants of the district into the area mentioned in (b). Each plot was considered "urban" or "rural" according to the following criteria: urban = population density  $\geq 400$  persons/km<sup>2</sup> where more than 50% of the population do not live in a farming environment (based on the census of current population, Federal Statistical Office Germany 2006). All other plots were classified as rural. Four "microhabitats" per plot were identified: human-populated area (neighbourhood), cemeteries, parks and industrial areas.

We used *A. altissima* density (individuals per hectare) as the response variable for all analyses. We used Kruskal Wallis and post-hoc LSD-test to determine whether the size categories of train stations affect the number of individuals of *A. altissima* per hectare. By linear regressions we tested if the urban gradient (indicated by the total human inhabitants per square kilometer) and the altitude affect the number of individuals per hectare of *A. altissima*. By one way ANOVA we assessed whether the abundance of *A. altissima* changes between micro habitats. However, due to the low number of plots with presence of *A. altissima*, the microhabitat variable was collapsed as follows: neighbourhoods and green areas.

All these calculations were made for: all individuals combined and for individual size category separately.

### 3.3 Results

#### 3.3.1 Train Stations

From the 234 train stations, almost three quarters (172 stations) had no individuals of *A. altissima* implying no risks induced by this plant during this study there. Meanwhile, *A. altissima* was present only in 62 stations.

Of all individuals found (6944), 55% were small plants between 1 cm-height and 1cm dbh, 44% were individuals between 1-10 cm dbh and only 1% were trees > 10 cm dbh. From the 62 stations where *A. altissima* was present, the species was found as small plants in 59 of the 234 stations, as saplings and young tree in 53 of the 234 railway stations and as large trees in 27 of the 234 railway stations.

All stations studied averaged 326.20 (SE=  $\pm 78.81$ ) individuals (n = 234). Thus, 48 stations had between 1-100 individuals, whereas 14 of the stations recorded more than 100 individuals (Fig. 4)

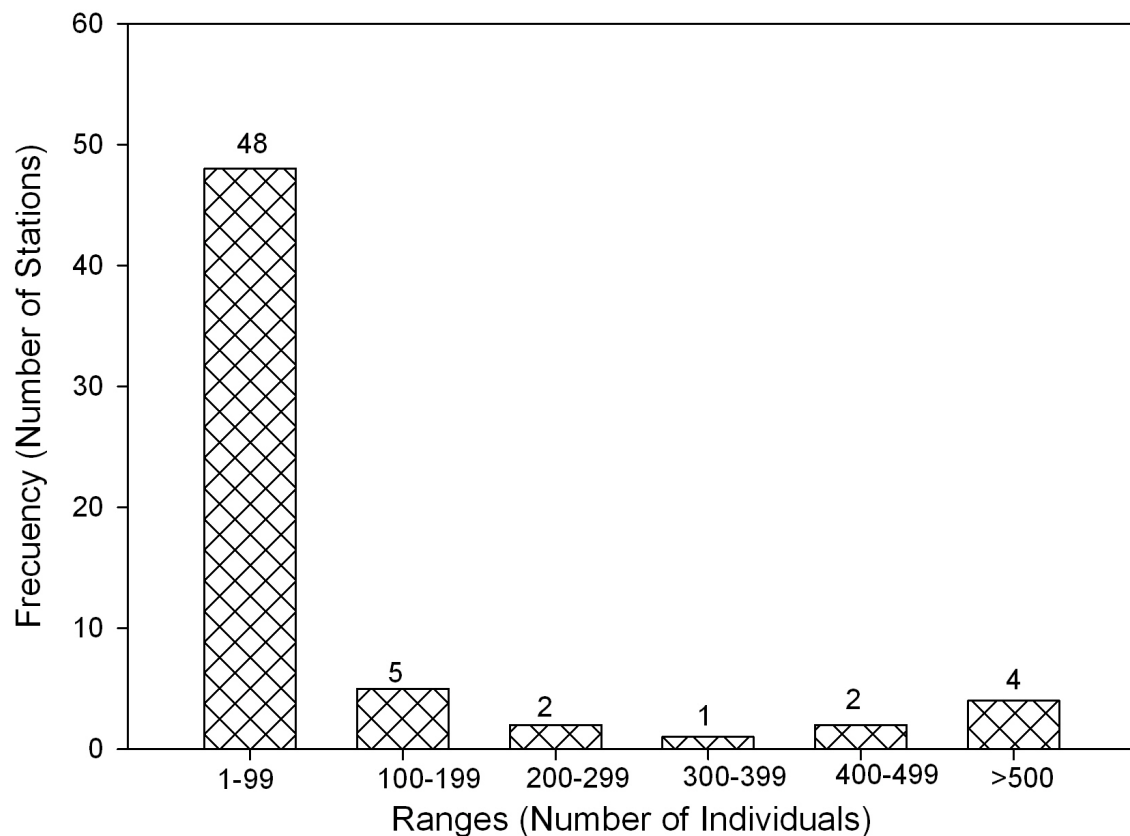


Figure 4 Frequency (number of stations) where *Ailanthus altissima* was found and abundance of the species.

The train station of Wiesbaden (capital of Hesse) had the largest total number of individuals (1460) followed by Frankfurt central station (1091 individuals) and Hanau (929 individuals). Wiesbaden central station had also the highest small plant population (1118 small individuals), followed by Hanau (621 small individuals) and Frankfurt central station (363 small individuals). Frankfurt central station also shows the highest number of saplings and young trees with 725 followed by Gross Gerau (383 saplings and young trees). The greater abundance of large trees was reported in Hanau (12 large trees), followed by Frankfurt West (11 large trees). Notice that all these stations are located in southern Hesse; in contrast, the northern

region had virtually no-individuals (between 0.1-0.5 % of the 6944 individuals for each station).

The size of the stations was related to the abundance of *A. altissima* (KW4, 228=28.21,  $P<0.001$   $n=233$ ). Specifically, stations category 2 averaged 1122.28 (SE=  $\pm 38.49$ ,  $n=7$ ) individuals thereby having five- and four times more individuals of *A. altissima* than station categories 5 (average=  $230.75 \pm 26.39$ ,  $n=62$ ) and 6 (average= $276.35 \pm 36.90$ ,  $n=130$ ), respectively. Meanwhile, stations categories 3 and 4 averaged 470.04 (SE=  $\pm 39.18$ ,  $n=11$ ) and 496.69 (SE=  $\pm 32.77$ ,  $n=23$ ) individuals, respectively (Fig. 5). There was only one station category 1 (Frankfurt central station) and it was excluded for the calculations.

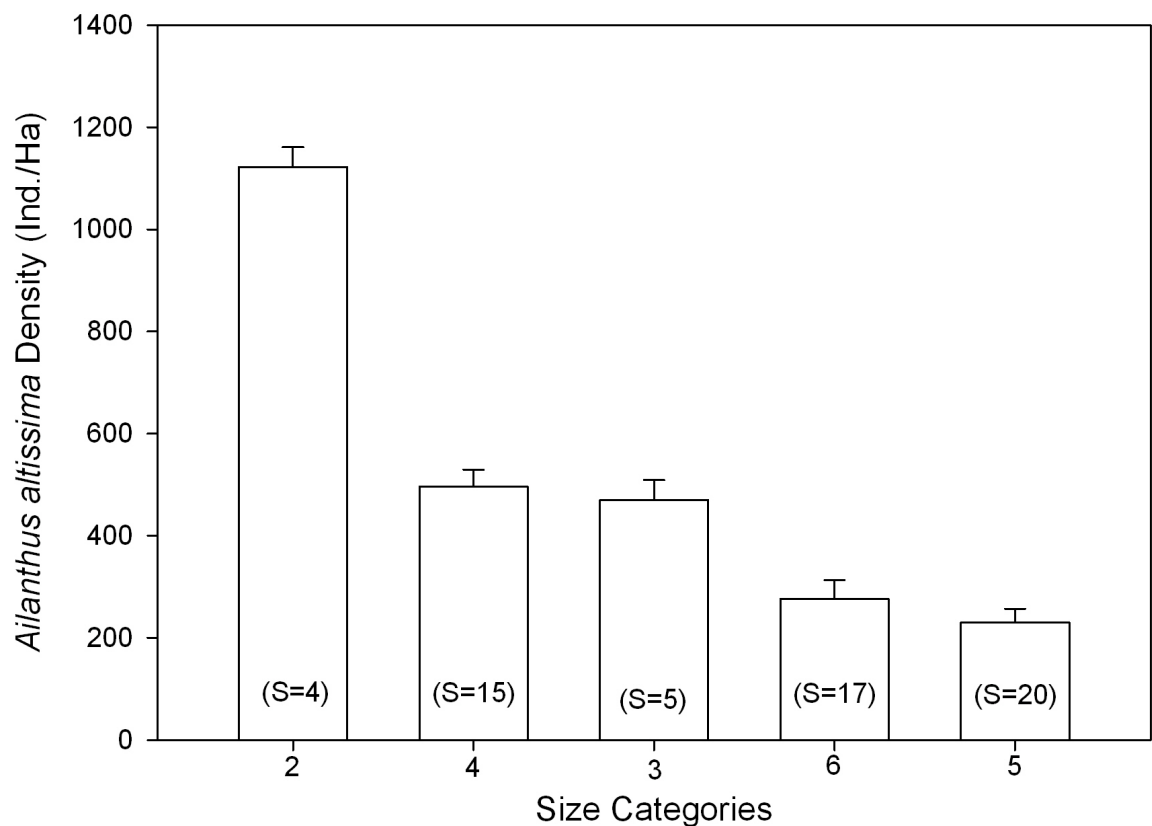


Figure 5 *Ailanthus altissima* Densities (Individuals per hectare) per Size Categories of the train station. Here S represents the frequency of the stations.

### 3.3.2 Urban gradient

*Ailanthus altissima* was found in 56% (14 of 25) of the plots visited. Combining all plots, this represented a total of 8429 individuals. The abundance of *A. altissima* is higher in large cities like Frankfurt and decreases towards and in the forested areas of Taunus; the only places in the Taunus region having individuals of *A. altissima* are human-populated areas like Oberursel (Fig. 6).

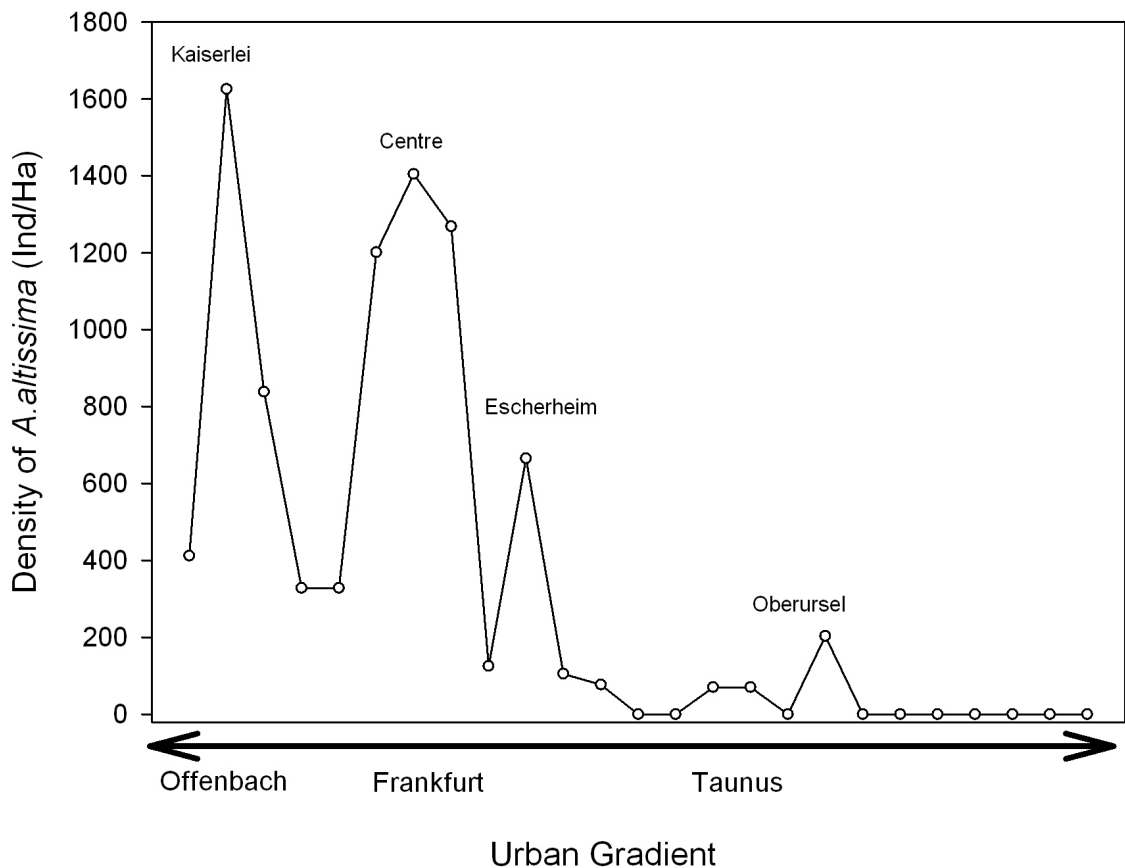


Figure 6 Plots urban rural gradient where *Ailanthus altissima* was studied. More number of individuals per hectares was present in the big cities and this density decreased closer to the forested areas.

For all plots combined, microhabitats having more human-populated areas (neighbourhoods) had the highest number of *A. altissima* individuals (6974)



of the total found, followed by parks with 945 individuals, industrial areas with 348 individuals and cemeteries with 162 individuals. On average, neighbourhoods had 5.2 times more seedlings and small sapling individuals than green areas (One-way ANOVA,  $F_{19,17}=6.081$ ,  $P=0.019$ ). Similar patterns occurred for large saplings (One-way ANOVA,  $F_{19,17}=6.006$ ,  $P=0.020$ ) and trees (One-way ANOVA,  $F_{19,17}=7.148$ ,  $P=0.011$ ). The neighbourhoods averaged 4.3 times more large saplings and juveniles of *A. altissima* than the green areas, whereas for trees the neighbourhoods had much more (12.2 times) more adult *A. altissima* trees than the green areas (Table 1).

Table 1 Averaged ( $\pm$  Standard Error) number of individuals for three size classes of *Ailanthus altissima* for neighbourhoods and green areas of the State of Hesse, Germany.

	Neighborhoods	Green areas
Seedlings and small sapling	232.26 ( $\pm 17.51$ )	44.65 ( $\pm 8.19$ )
Large saplings and juveniles	121.58 ( $\pm 12.25$ )	28.18 ( $\pm 6.95$ )
Tree	28.74 ( $\pm 6.35$ )	2.35 ( $\pm 5.43$ )

Increased human population density, produces an increase in the density of *A. altissima* individuals. This pattern is more remarked for trees ( $R_2 = 0.43$ , Fig. 7) than for all other categories ( $R_2 \leq 0.35$ , Table 2), though the pattern remains even for seedlings and small saplings ( $P=0.001$ , significant  $\alpha=0.05$ , Table 2). The most reliable model was obtained for *A. altissima* trees (see  $R_2$  in Table 2) but there were wide dispersion of the points (low  $R_2$ -values, see also Fig.7) reflecting data variance s not related to human population density but to other factors (e.g. microhabitat).

Table 2 Linear regression results for human population density vs density of *Ailanthus altissima* individuals for n=25- 18 hectare plots in the State of Hesse, Germany.

Size categories	Average $\pm$ ES (Standard Error)	F	R <sup>2</sup>	p
Seedlings and small sapling	11.49 $\pm$ 4.19	10.39	0.31	0.004
Large saplings and juveniles	6.15 $\pm$ 3.06	13.87	0.38	0.001
Tree	1.30 $\pm$ 1.46	18.30	0.44	0.000
All categories together	18.65 $\pm$ 5.34	12.60	0.35	0.002

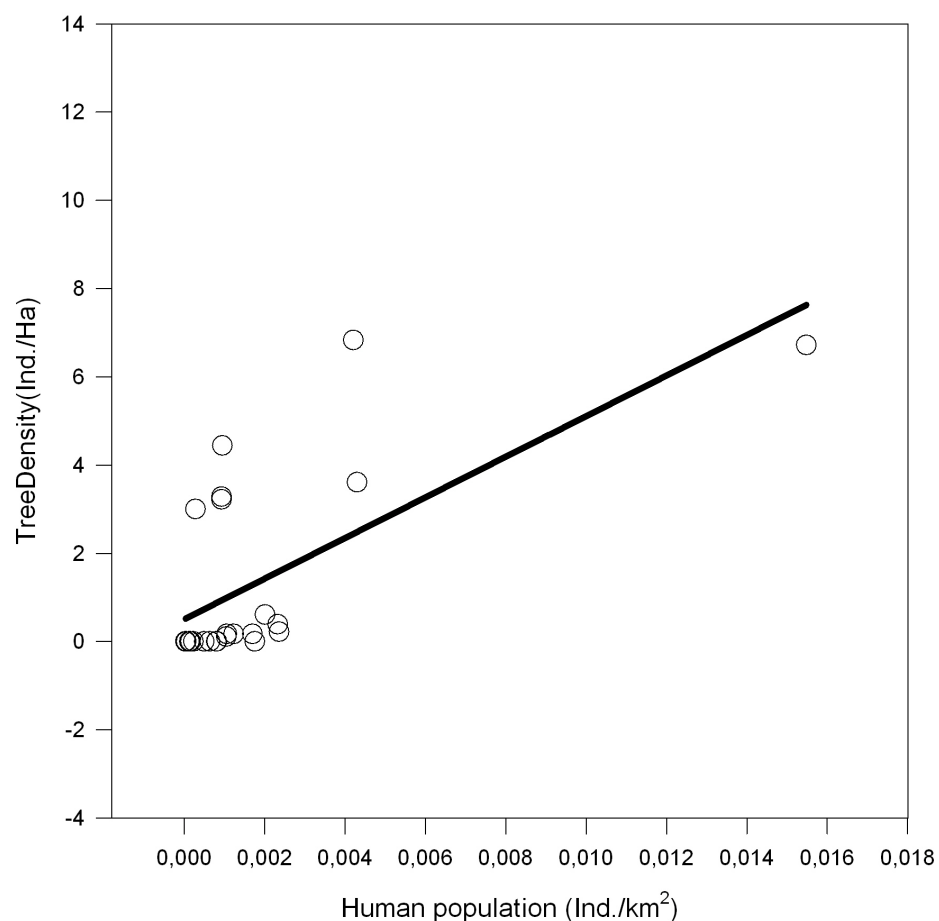


Figure 7 Tree density vs intensity of urbanism (Human population density) for *Ailanthus altissima* in Hesse, Germany.

Model: Tree density= 0.055 + 870.52 \* Human population; R<sub>2</sub>=0.44, P<0.001, in n=25- 18 hectare plots.

### 3.4 Discussion

#### 3.4.1 Train stations and cities

The larger abundances of *A. altissima* in larger train stations and larger cities in respect to small train stations, villages and forest areas are consistent with data presented by Kowarik & Böcker (1984), Gütte *et al.* (1987), Müller (1987), Punz (1993), Feder (2001), Punz *et al.* (2004). Railways and cities are open areas with cement, metal and stones; exposed to altered illumination and temperature compared to the ones where native species usually grow (see also Wittig 1998). It is too early –however, to consider that *A. altissima* proliferates in large train stations and cities because of its resistance to environmental stress since this remains experimental and not fully studied. Oberursel seems to be an urban threshold in the distribution of *A. altissima*, but Oberursel is only 197 m. a. s. l. and had a population density of 952 ind/m<sup>2</sup>. Altitude was not considered as an explanation reason in this study, because there was not an extreme variation in altitude. In Hesse altitude changes were in ranges from 0- to 800 meters, at this respect, some authors place the altitudinal distribution range of this species between 0-2000 m. a. s. l. (Hu 1979; Feret 1985; Singh *et al.* 1992; Schäfer 2003; Howard 2004). There are also synergisms among environmental factors (e.g. drought, temperature and illumination) and between such factors with other aspects (e.g. resistance to drought; Rejmánek & Richardson 1996, Alpert *et al.* 2000) making it difficult to predict which environmental conditions effectively favours *A. altissima* in respect to other species. Climate determined range seems to be colonized, but global warming may enhance further range expansion of this species due to increasing warmer locations in

larger European cities. Besides resistance to the environment, higher abundances of *A. altissima* can also result from the immigration of seeds by means of the directional strong winds generated at train stations and by “accidentally” carrying seeds between the wheels and other structures of trains and cars. Unfortunately, this remains untested because it is prohibited to look closely at the train structures for security reasons. Further studies are necessary to quantify the relative importance of survival to environmental stress vs. high immigration of propagules as determinants of the high abundance of *A. altissima* in large train stations and cities. The pattern we found –however, confirms the necessity of keeping control practices in large train stations to tackle the spread of *A. altissima* to other areas.

Our results in train stations and cities reveal a paradox: the public and private sector of Hesse spend millions of Euros to control invasive plants like *A. altissima* and even German Railways administration (Deutsche Bahn) spends 18% of its budget on weeding just to control this species (Lezcano-Cáceres & Gerold 2009). Large train stations and cities have a very intense economic activity supplying a big stake of the income for companies like German Railways administration (Deutsche Bahn) but are also places demonstrating large abundances of invasive species for which they are trying to control. There appears to be a feedback process fuelling this problem: the train company controls *A. altissima* along the railways but seeds can come from the surrounding neighbourhoods as well as the propagules related to train stations can colonize into those neighbourhoods. This implies the necessity for both private and public sectors to coordinate their efforts to control *A. altissima*.

Interestingly, we found more *A. altissima* in southern Hesse compared to the north. Different authors have attributed this to the change of microclimate and the number of summer days related to the Harz Mountains which in turn generate less favourable growing conditions for *A. altissima* in the north (Kramer 1995, Kowarik & Böcker 1984). We propose that, together with this, there is also an effect of urbanism –including intensity of train and car traffic and concentration of human settlements. Specifically, there are more than 100 urban centres in southern Hesse –mainly related to the City of Frankfurt, but no more than 30 in northern Hesse. Thus, the higher abundance of *A. altissima* in the south may also reflect the success of this plant in urban environments.

### **3.4.2 Urbanism**

Also we found more *A. altissima* in neighbourhoods compared to those of green areas such as parks and cemeteries, other studies have demonstrated a similar pattern (Kowarik & Böcker 1984, Kowarik 1995, Kramer 1995). Since neighbourhoods are open areas with plenty of cement, they also comprise many microclimatic aspects favouring *A. altissima* (e.g. altered illumination and temperature) and are able to receive many seeds. When one environmental change, this can determine, in part, the steepness of the gradient in structure and function. In this sense, interaction between environmental gradient and the ecological system will affect the distribution and behaviour of the system along gradient (Terborg 1971, Robert 1987).

Indeed, we support explanations largely formulated by other authors saying that such conditions make *A. altissima* to be more abundant in neighbourhoods than in green areas (Sargent 1888, Wittig 1998, Kramer 1995, Rank 1997, Nesterovic & Jovanovic 2003) as well as we support the explanation as to why *A. altissima* was more abundant in larger cities of our study.

Once again –however, the latter remains experimentally poorly explored and we propose two complementary explanations. (1) Grass is grown on green areas but such grass out-competes *A. altissima* individuals (Lezcano-Cáceres, in prep.). (2) Green areas like cemeteries and parks are submitted to periodic, planned weeding following plans organized by local governments in a centralized way. Moreover, visitors of cemeteries also often weed plants like *A. altissima* growing around the gravels of their deceased love ones. In fact, the open areas around parks and cemeteries usually have *A. altissima* juveniles and trees (Lezcano-Cáceres, pers. obs.) suggesting that there are sources of propagules able to migrate into the green areas and that if such propagules do not prosper, it is because of weeding. Thus intensive and planned weeding may help to explain why we find less individuals of *A. altissima* in green areas. In the neighbourhoods by contrast, each garden is maintained by an independent family implying the lack of a planned weeding strategy. For example, some garden owners may prefer to let *A. altissima* grow, even confusing them with other species like *Rhus hyrta* (Anacardiaceae, german common name is “Essigbaum”).

### 3.5 Conclusion and recommendations

Our study confirms that *A. altissima* is a species pre-adapted to urban environments: its abundance is related with human population concentration in large cities and their cultural practices, because they produce change in the ecosystem and it can influence the behaviour of the individual present on it, favouring its dispersion or distribution, better competition have better chance to develop their populations, in this sense *A. altissima* was planted after WWII in severely destroyed cities of Germany and then started spread to other areas but nowadays it proves itself as a strong invasive species. In order to control *A. altissima* we recommended pruning the mature trees before they start to flower (from July to August) in order to stop seeds production. To control the spread and distribution of *A. altissima*, we recommended a combined control strategy coordinating the Train Company, city governments and private gardens of the citizens in order to avoid propagules from such sources to migrate into other potential areas. This will help to reduce potential money losses for both government and the Central Train Administration (Deutsche Bahn), as well as helping to protect local plant communities in Germany and other European countries where *A. altissima* is shown to be a strong invader.

## CHAPTER 4

### ***Ailanthus altissima* (Mill.) Swingle growing in different substrate types and seed densities: substrate and competition as reasons for an invasion in the south-central Germany.**

#### **Summary**

The soil condition and competition are two major factors affecting the germination and subsequent growth of plants during their initial establishment phase. *Ailanthus altissima* is recognized as a successful invasive tree species partly because of its high germination and growth rates. The species occupies many different places, outcompetes other tree species and its roots uplift building foundations, streets and sidewalks and can cause cracking, rupture of water canals and removal of railways at train stations, all contributing to money being lost for public and private agencies. We studied the germination and growth rates of *A. altissima* which were experimentally planted on different substrate types (bare soil, gravel and soil covered with grass having nine plots for each substrate. For each substrate, we had  $n=3$  plots with the following densities: 100-, 150- and 200 seeds per square meter totalizing 27 plots. The study was conducted in the Botanical gardens of the Johann Wolfgang Goethe University during the summer of 2006. The results showed higher germination percentage ( $64.3 \pm 3.0\%$ ;  $p = 0.0001$ ) and relative growth rates ( $17.22 \pm 0.68$  cm;  $p = 0.0001$ ) when *A. altissima* was sown in bare soil with the highest density (200 seeds/m<sup>2</sup>) compared with other treatments. However, when *A. altissima* was planted in bare soil to the



lowest density (100 seeds/m<sup>2</sup>), root length, stem-basal area and growth rate based on dry weight were higher than in other treatments. On the soil covered with grass, *A. altissima* showed the lowest germination percentage ( $2.0 \pm 0.6\%$ ) and it even did not germinate under higher seed densities.

Root shoot ratio indicates that *A. altissima* invests more of its growth resources into the production of roots and less of its growth resources into producing leaves and stems in gravel at high seed densities which in turn guarantees its establishment by means of reaching soil resources in comparison with soil for both factors (treatment  $F_{1, 12}=11.47$   $p=0.005$  and density  $F_{2, 12}=11.91$   $p=0.001$ ) and for the interaction of these two factors ( $F_{2, 12}=9.30$   $p=0.004$ ).

The high germination percentage and its relative fast growth rate are strong characteristics of this invasive species which it in turn uses to colonize open places near - and in cities and demonstrate its strong fixation in its rooting process which will help guarantee the species to survive in these places. After drying, the plants lost between 77 - 78% of their wet weight, indicating a high water absorption in the early stages of the plant growth.

## 4.1 Introduction

*Ailanthus altissima* (Mill.) Swingle (Simaroubaceae) is a species native to eastern China where it is a pioneer tree; the species opportunistically thrives in full sun on disturbed areas. *A. altissima* grows as fast as one- to two meters per year during the first four years of its life (Howard 2004). The

species also aggressively spreads; do to its high seed-production and vegetative sprouting from roots and stems that grow quickly after being cut during control practices (Miller *et al.* 1965, Call & Nilsen 2003). Due to all these, *A. altissima* has successfully invaded the Centre of Europe, North America, South Africa and Argentina among other areas.

Seeds of *A. altissima* collected by hand and then dried achieve a germination rate of 60 - 85% in laboratory conditions (Miller 1990, Vines 1960). Hunter (1989) reported a rate of 30% germination of seeds that remains on the tree during winter and disperses or collected in the following spring. In a greenhouse experiment, the germination rate was lower in sand (55 %) than in rubble (69 %) and peat (71 %) substrates (Hildebrand 2006). It is known that *A. altissima* -seeds can germinate in very compacted soil (Rabe 1985, Pan & Bassuk 1985), that the embryos of *A. altissima* are able to stay dormant and stratification improves germination rates (Graves 1990, Hunter 1989, Miller 1990), and that the species establishes a temporarily short seed bank with high seed viability (Zasada & Silas 2002). A recent study demonstrated that the percentage of germination on soil is 53% and increases to 87% after 3 days of humidity treatment (Kowarik & Säumel 2006b). *A. altissima* grows well on gravel (Kramer 1995). There are no reports of its germination and development of the species on areas covered by grass in spite of well recognized abundance of *A. altissima* on urban areas covered by grass. This inconsistency makes difficult to know if grasses are potential, inter-specific competitors inhibiting *A. altissima*'s proliferation.

The literature about competition has long being dominated by the Grime-Tilman debate (Tilman 1985, 1987, 1998; Tilman & Cowan 1989, Grime 1979, 1988, Grime & Hodgson 1987, Thompson 1987, Thompson & Grime 1988). These authors disagree about the traits of successful competitors and about the importance in nutrient-poor environments. Moreover, there is still much discussion about how the plants allocate their biomass as a result of competition- and substrate-induced stress and about the relative importance of above and below-ground competition for the outcome of competitive interactions (Aerts 1998). For example, it has been shown that the germination and development of *Gossypium hirsutum* (L.) and *Parthenium argentatum* Gray (Krieg & Bartee 1975, Foster *et al.* 1993) are affected by seed density. However no studies have been done to identify under which densities the germination and further development of *A. altissima* is limited by intra-specific competition.

Invasive species produce a loss of millions Euros every year (U.S. Congr. Off. Technol. Assess. 1993, Pimentel *et al.* 2000, Pimentel 2002, World Bank 2002, UFZ 2002, Cock 2003, Andreu & Vilá 2007) and in the Federal State of Hesse, Germany, *A. altissima* produced losses of five Million Euros between 2006 and 2007 (Lezcano - Caceres & Gerold 2009).

In order to know how *A. altissima* used the resources offered to colonize specific places we design this experiment to answer these questions:

Is *A. altissima* germination high or low?

Exist an intra-specific competition depending on individual's density?

Exist an inter-specific competition when other species is present in the substrate?

How is *A. altissima* germination percentage and RGR growing on different kind of substrate?

Due to the high invasive power *A. altissima*, is necessary to know seed germination percentage and seedling growth rates in different types of substrates and their density conditions in order to recommend management strategies to control populations of this species in and around cities where it has its fullest impact felt.

## **4.2 Methods**

### **4.2.1 Research plots**

A total of 27 plots (1 m<sup>2</sup>) were established in the Botanical Garden of the Johann Wolfgang Goethe University during the summer of 2006 in order to assess the germination percentage and the relative growth rate of *A. altissima*. The seeds were sown in three different types of substrate (bare soil, soil with gravel and soil covered with grass) and at three different densities (100, 150 and 200 seeds/m<sup>2</sup>).

After the start of the rainy season (April), the seeds were sown in each plot at 1 cm depth and fixed with toothpicks placed at the sides of the seed (without drilling any seed), to avoid them from being swept away by wind currents.

The plots did not receive irrigation other than natural rainfall. All plots were visited once a week for a period of three months to measure the percentage of germination and growth rate (longitudinal growth and basal area-changes).

After the third month, all plants were manually harvested and separated into roots, stems and leaves. The roots were washed with water to remove soil and other residues and then dried with paper towels. The length was measured and all wet components of the plant were weighed. Stems, leaves and roots were weighed separately with an analytical balance (Sartorius Model Ba-110). All materials were dried in a forced air oven at 90 °C (Heraeus type T6) for a two week period and at a constant temperature. Once dried, the weight of each individual shoot (stems and leaves combined) and roots were determined. The leaves were counted and the total leaf surface of each individual was determined with a LICOR-3100 Area Meter (Licor, Inc. Lincoln Nebraska, USA).

With the data we calculated the germination percentage ( $\% = \text{germinated plant} / \text{total seed on the plot}$ ) and relative growth rate ( $\text{RGR} = \text{Final weight} / \text{Initial weight}$ ). To avoid spatial autocorrelation and pseudo replications, response variables were averaged for all seedlings that grew in each plot. We used the average as response variable in all variables studied. Two-way ANOVA were conducted ( $\alpha = 0.05$ ) to determine if there were differences in growth of *A. altissima* for the following treatments: substrate (three levels: bare soil, gravel and soil covered with grass) and density of planted seeds (three levels: 100-, 150- and 200 seeds.m<sup>-2</sup>). Mean differences were assessed using LSD analyses all response variables (germination, relative

growth rate of the plant based on plant length and dry weight, basal stem diameter, leaf number, total leaf surface-area and root: shoot ratio).

## 4.3 Results

### 4.3.1 Germination

*Ailanthus altissima* germination percentage ranged between 34 - 64% on bare soil and between 11-18% on gravel. Seeds planted in soil covered with grass had a low germination percentage ( $2.3 \pm 0.6\%$ ). Moreover, on soil covered with grass and sown with increased seed density there was no germination (Fig. 1).

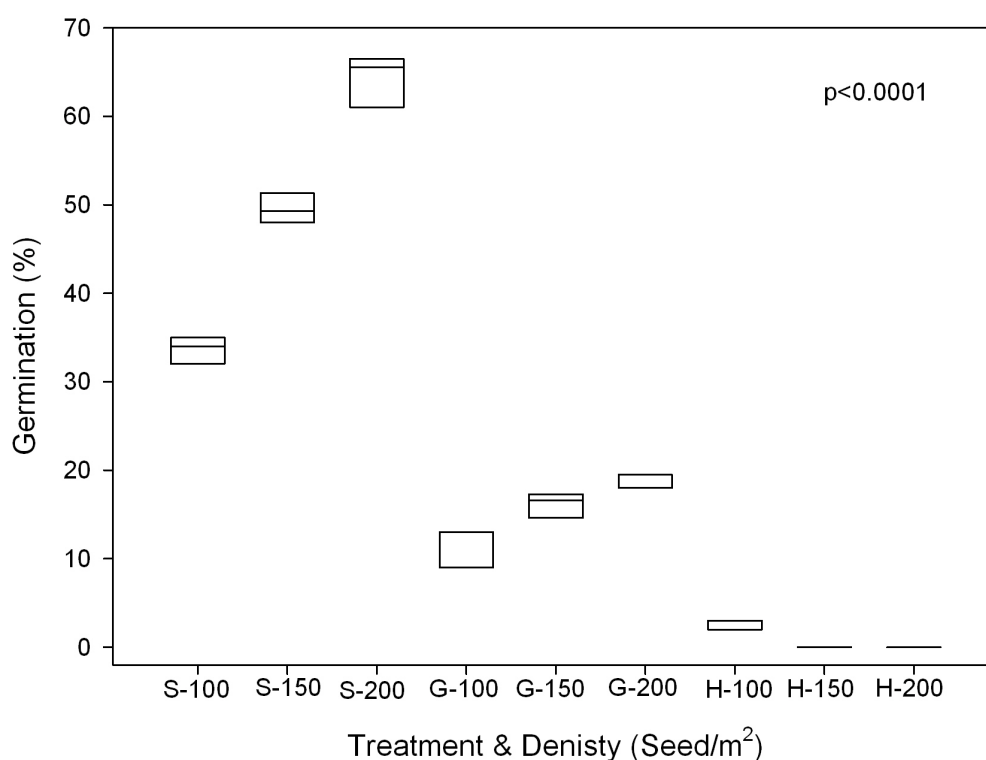
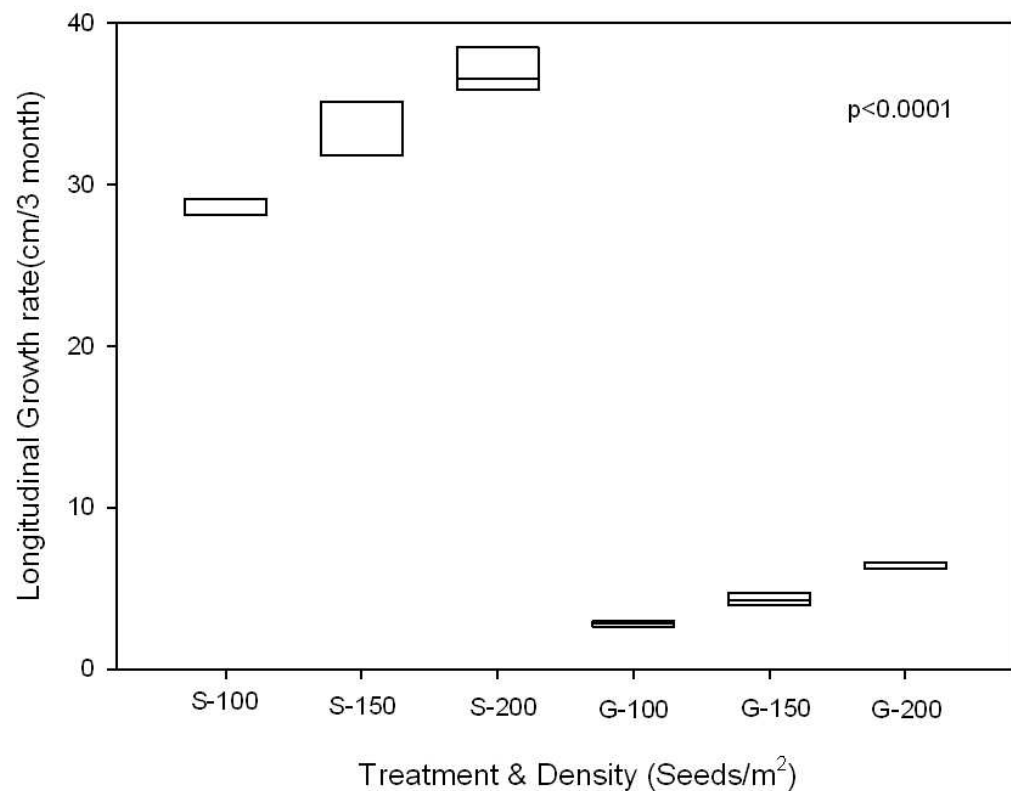


Figure 1 Mean germination percentage of *Ailanthus altissima* in different substrate types and seed densities. (S= soil, G=gravel and H= soil +grass). Seed densities per .m<sup>2</sup> are indicated by numbers 100, 150 and 200. Two-way ANOVA ( $\alpha=0.05$ ) \* = $p > 0.0001$ . For each box, n=3 plots.

#### 4.3.2 Relative growth rate (RGR)

The relative growth rate of *A. altissima* based on the longitudinal growth was better on bare soil and increased with increasing individuals density ( $S_{200}$  Average=  $147.87 \pm SE\ 5.48\ cm/3month$ ). Similar results were obtained for gravel ( $G_{200}$  Average=  $25.88 \pm SE\ 0.91\ cm/3\ month$ ). On grass covered soil very few seeds germinated and they died after a few days. On soil covered with grass with higher seeds densities, there was no-germination (Fig. 2a). The relative growth rate (RGR) based on dry weight of the plant was higher for seedlings growing on bare soil with a lower seeds density ( $S_{100}$  Average=  $22.59 \pm SE=0.43\ g/3\ month$ ) and the values decreased with increasing seeds density.



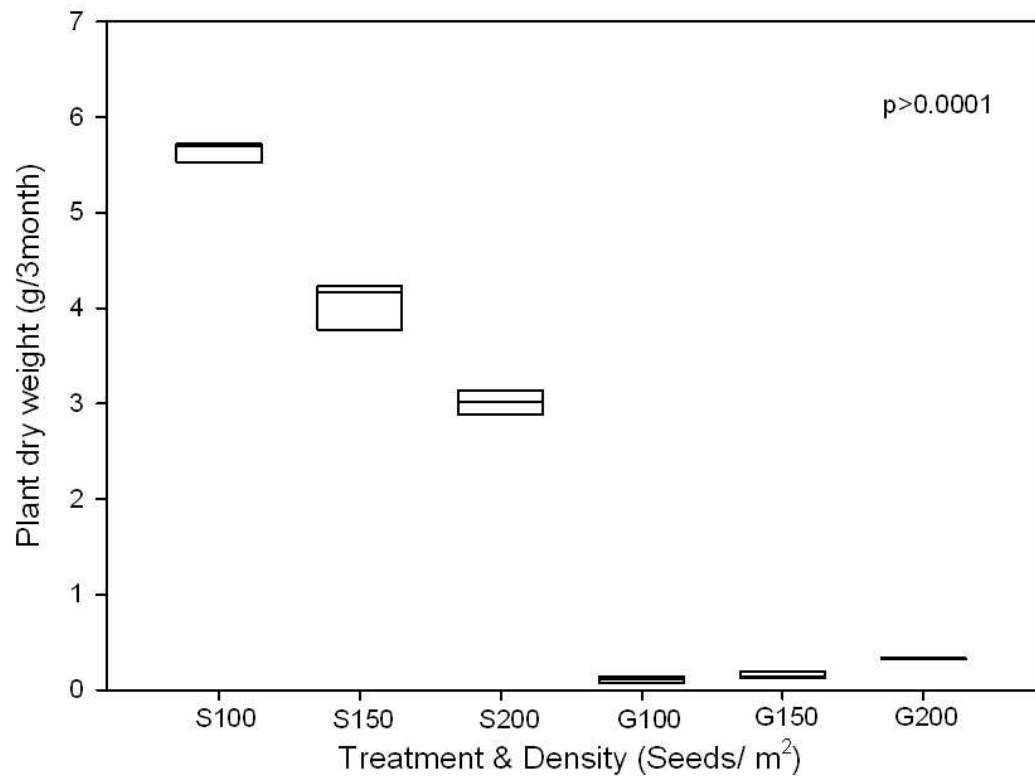


Figure 2 Relative Growth Rate of *Ailanthus altissima* based on a) longitudinal growth (cm/3month) and b) aerial dry weight (g/3month) under different substrate types and seed densities. (S= soil, G=gravel) and for different seed densities (100, 150, 200 seeds.m<sup>2</sup>). Two-way ANOVA ( $\alpha=0.05$ ) \*  $p > 0.0001$ ,  $n=3$  plots for each box.

On gravel, the pattern was the opposite with increasing RGR values where the seed density increased ( $G_{200}$  Average=  $1.32 \pm SE 0.02$ g/3 month, Fig.2b) although the RGR based on dry weight for seedlings on gravel was always less than on bare soil. On grass covered soil covered, data was not collected because the plants died. In all cases the results are statistically significant  $p < 0.001$  for the interaction density x treatment.



### 4.3.3 Root elongation

The longitudinal root growth was better for seedlings on bare soil with 100 planted seeds per square meter ( $S_{100}$ ; average = 27.33;  $\pm$  SE= 0.58 cm), with a reduction of root length with increasing densities. The opposite pattern was observed on gravel, where there was an increase of root length with increasing densities; there the highest RGR was reached by seedlings growing on gravel with 200 indiv.m<sup>-2</sup> ( $G_{200}$ ; Average= 13.40,  $\pm$  SE= 0.01 cm; Fig.3). In the case of grass covering soil, no data was collected, because all germinated plants died.

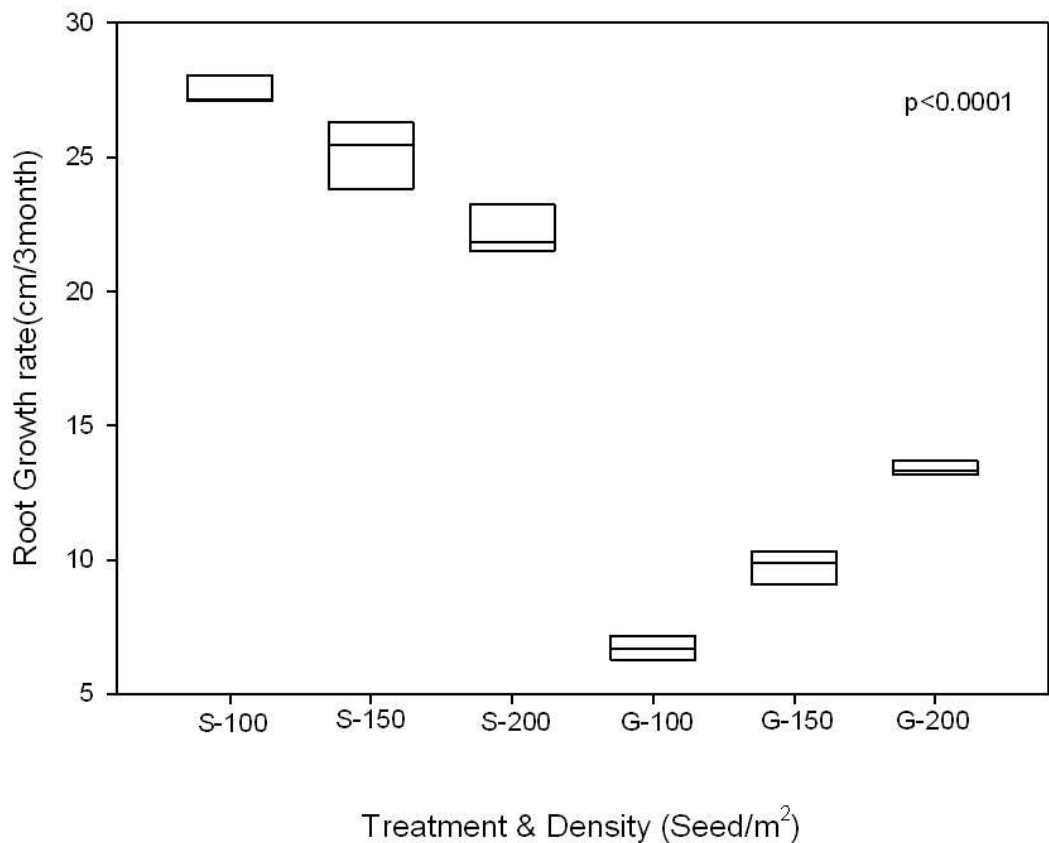


Figure 3 Mean root length of *Allanthurus altissima* under different substrate types and seed densities.

(S= soil, G=gravel) and for different seed densities (100, 150 and 200 seeds.m<sup>-2</sup>). Two-way ANOVA ( $\alpha=0.05$ ) \* = $p > 0.0001$ . For all boxes,  $n=3$  plots.

#### 4.3.4 Stem basal diameter

The values of seedlings' stem diameters in bare soil were higher at lower seed density ( $S_{100}$ , Average =  $0.71 \pm SE = 0.02$  mm); such values decrease with increasing individuals density. The opposite pattern was observed for seedlings on gravel ( $G_{200}$ , Average =  $0.22 \pm SE = 0.01$  mm, Fig 4). There were no data for seeds planted on soil covered with grass, because there was no germination or the individuals died.

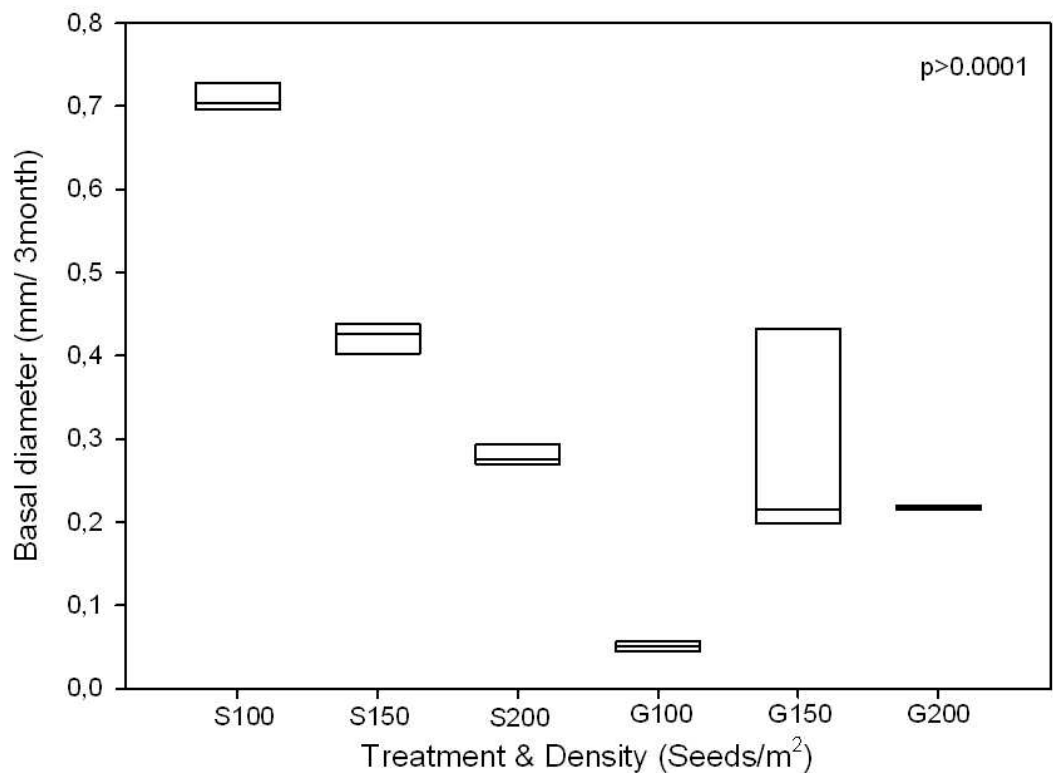


Figure 4 Mean basal diameter of *Ailanthus altissima* under different substrate types and seed densities. (S= soil and G=gravel) and for different seed densities (100, 150 and 200 seeds.m<sup>-2</sup>). Two-way ANOVA ( $\alpha=0.05$ ) \*  $p > 0.0001$ . For each box, n=3 plots.

#### 4.3.5 Leaf number

The number of leaves per individual was higher for plants grown on bare soil with lower density of individuals ( $S_{100}$ , Average =  $8.34 \pm SE = 0.12$ ). On gravel, the individuals had more leaves when growing on plots with higher individuals densities ( $G_{200}$ , Average =  $12.09, \pm SE = 0.72$ ) and the values decreased as density of plants decreased (Fig. 5).

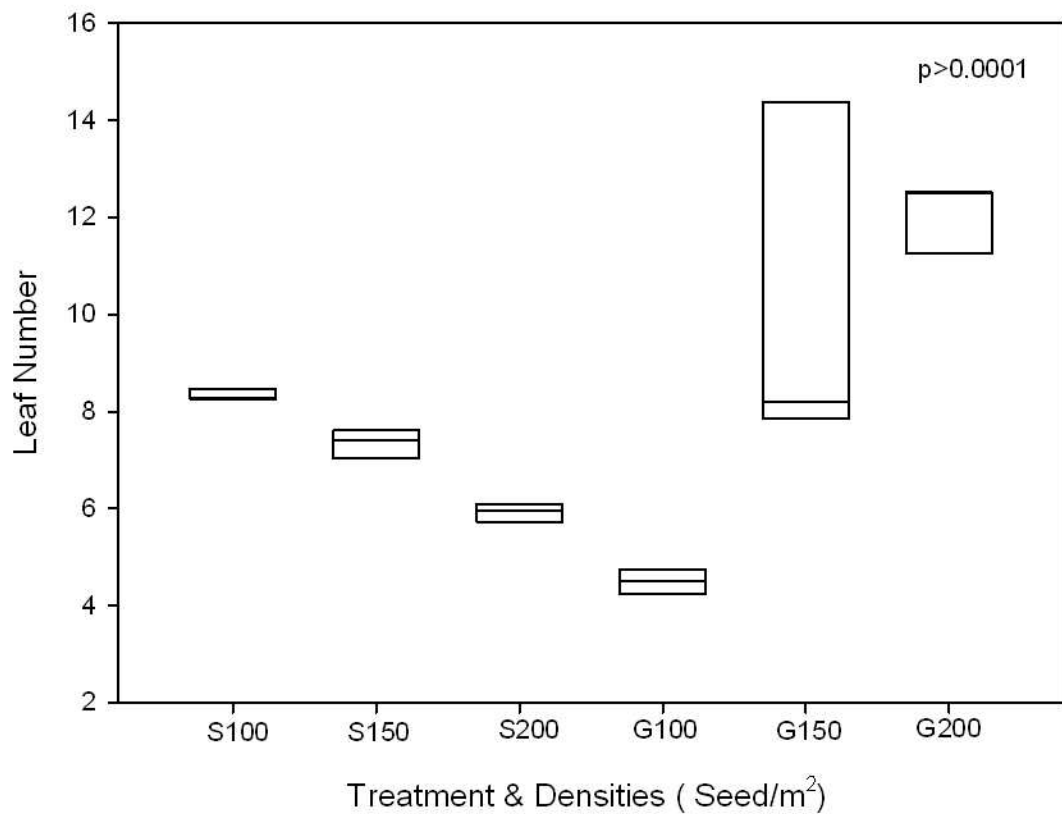


Figure 5 Mean leaf number of *Ailanthus altissima* seedlings under different substrate types and seed densities.

(S= bared soil and G=gravel) and for different seed densities (100, 150 and 200 seeds.m<sup>2</sup>). Two-way ANOVA ( $\alpha=0.05$ ) \* = $p > 0.0001$ . . For each box, n=3 plots.

#### 4.3.6 Superficial leaf area

Superficial leaf area was higher for plants grown on bare soil with lower individuals' density (S<sub>100</sub>, Average = 80.67,  $\pm$  SE = 1.55 mm<sup>2</sup>). On gravel, the best results were obtained for plots with higher individual densities (G<sub>200</sub>, Average = 45.00,  $\pm$  SE = 3.46 mm<sup>2</sup>). There were no data in grass covering soil because plants died or did not germinate (Fig. 6).

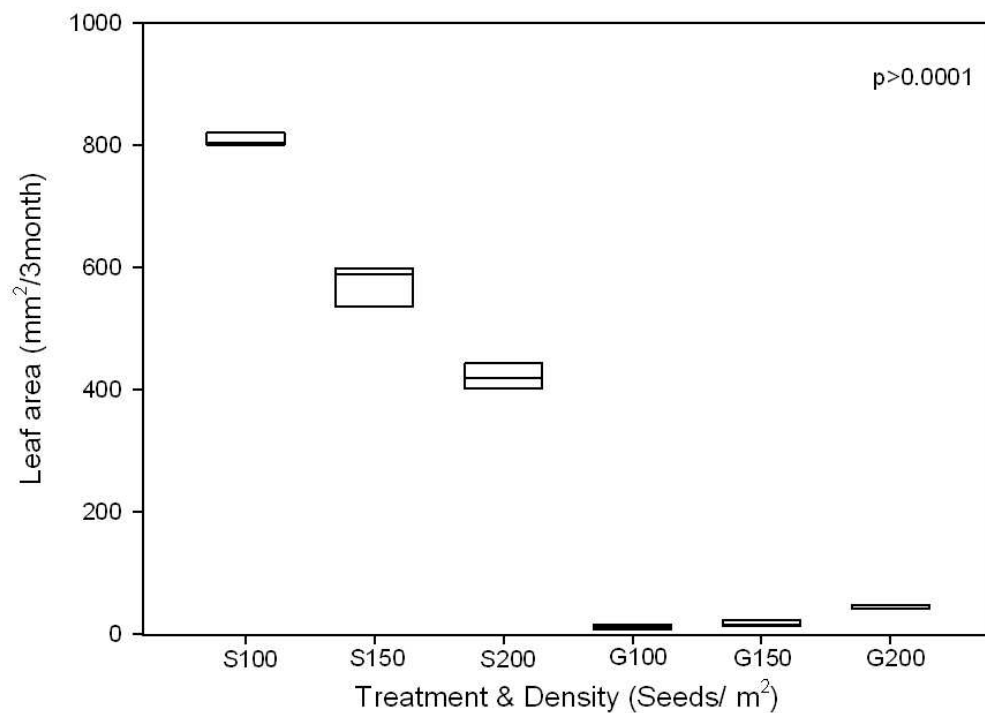


Figure 6 Mean superficial leaf area of *Ailanthus altissima* under different substrate types and seed densities. (S= bare soil, G=gravel) and for different seed densities (100, 150 and 200 seeds.m<sup>-2</sup>). Two-way ANOVA ( $\alpha=0.05$ ) \* = $p > 0.0001$ . For each box, n=3 plots.

#### 4.3.7 Root: shoot ratio

In general, the root to shoot ratio was higher for plants growing on gravel compared to bare soil (two-way ANOVA,  $F_{1, 12}=11.47$   $p=0.005$ ), suggesting that plants growing on gravel invested more biomass for root development in respect to the shoot development (Fig.7). The root to shoot ratio was also affected by the density of planted individuals ( $F_{2, 12}=11.91$   $p=0.001$ ) and the substrate  $\times$  density interaction factor ( $F_{2, 12}=9.30$   $p=0.004$ ). On the gravel, there was a clear pattern of higher biomass investment by seedlings to produce roots in respect to shoots when the density of surrounding individuals increased (Fig.7). Interestingly, on the bare soil, there was a reduction of such investment for seedlings planted in densities of 150 ind.m<sup>-2</sup> compared to 100ind.m<sup>-2</sup>, but when the density was increased to 200ind.m<sup>-2</sup>, seedlings had higher root to shoot ratios. The latter suggests a switch from a density inducing relatively more investment in shoot production (150ind.m<sup>-2</sup>) to another where the seedlings invested more on root production (200 ind.m<sup>-2</sup>).

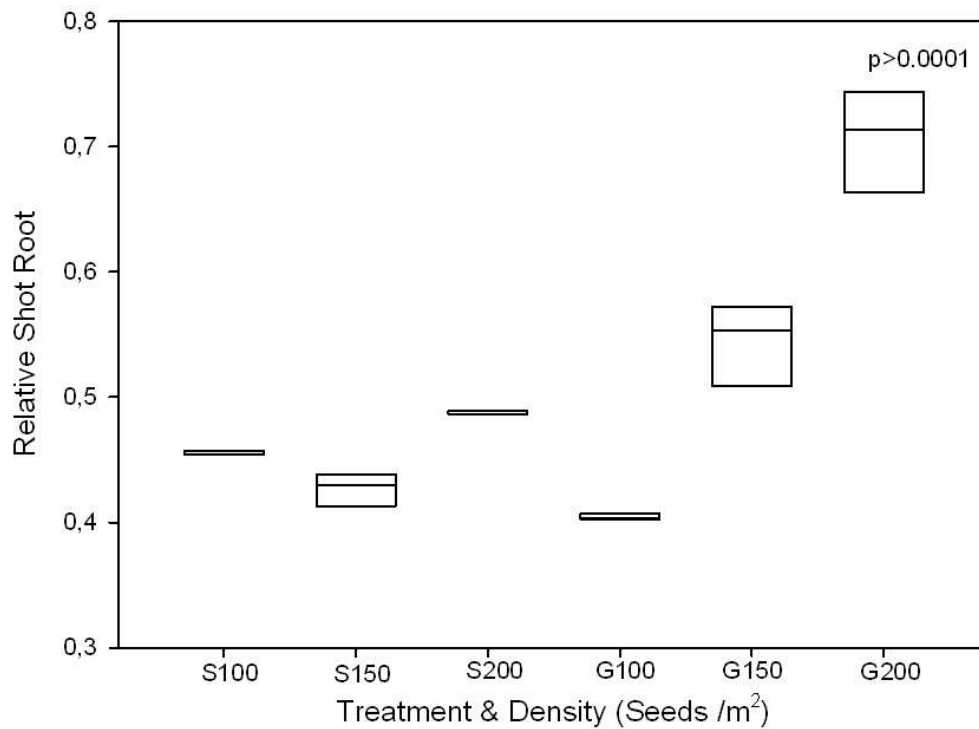


Figure 7 Root: shoot ratio of *Ailanthus altissima* under different substrate types and seed densities. (S= bared soil and G=gravel) and for different seed densities (100, 150 and 200 seeds.m<sup>2</sup>). Two-way ANOVA ( $\alpha=0.05$ ) \* = $p> 0.0001$ . For each box,  $n=3$  plots.

#### 4.4 Discussion

Our results suggest that the germination, growth and further proliferation of *A. altissima* are better enhanced by bare soils found in cities than by grasses and gravel. Latter is non-consistent to other authors saying that cement structures contribute to the proliferation of *A. altissima* (Kramer 1995, Hoshovski 1986, Kowarik 1995, Gover *et al.* 2004), but it is experimentally tested that *A. altissima* responds better than other native tree species in sand (Call 2000, Call 2002, Kota 2005), in soil (Lawrence *et al.* 1991) but studies with gravel were still not conducted. Our results also suggest that crowded densities of *A. altissima* seedlings generate intra-specific competition

potentially reducing the population growth of *A. altissima* by means of further death of “bad competitors” and that plants respond to such challenge by investing more energy and biomass to produce roots than shoots. Latter is an integrative explanation of the results occurring for the germination, growth and root to shoot ratios of *A. altissima* in our experiments. We will further discuss the details of such effects and some of their possible mechanisms.

#### **4.4.1 Substrate effect**

##### **4.4.1.1 Effect of substrate on *Ailanthus altissima* individuals**

Germination, RGR based on length, dry weight, root length, stem basal diameter and the leaf area, were better in a bare soil substrate compare with all other treatments.

The conditions offered in bare soil are more favourable for seeds and seedling in comparison to gravel or soil covered with grass. In concrete, soil keeps more capillary-water than gravel, and is thermally more stable; all these make soil a place where more nutrients are offered to the plants in comparison with gravel or grass covering soil (Hewitt 2004).

##### **4.4.1.2 Effect of substrate on the different parts of the plant**

###### **4.4.1.2.1 Seeds germination**

Besides the above characteristics, bare soils are also exposed to high light entrance facilitating the germination of this pioneer species. We suggest that a non-direct evidence of such role of light was our lower germination and

survival rate on plots with grass. The presence of grass inhibits germination of *A. altissima*, probably by altering the ratio of red light / far-red light-wave lengths (Vazquez-Yanes & Orosco-Segovia 1986). Seeds of pioneer trees exposed to light with a red: far-red ratio of 0.2 (beneath forest canopy) or 0.5 did not germinate, while seeds exposed to light with a red: far red ratio of 0.9 or 1.0 (equivalent to gaps like our bare soil) germinate to about 70% (Vazquez-Yanes 1979, Vazquez-Yanes & Orosco-Segovia 1986).

#### **4.4.1.2.2 Aerial part**

In general, development of the aerial part of the plant was better in soil compared with all other kind of substrate. Stem elongation, stem basal diameter, leaf number and foliar surface are favourable to per nutrient abundance present in bare soil, water disposition and lower stress. Plant growth was fastest in bare soil compared with all other substrate types. *A. altissima* as pioneer species, uses resource disposition to grow fast and quickly establish itself to guarantee its survival. Authors state slow growth of plants growing in poor-nutrient soils like gravel (Pearson 1968, Grime & Hunt 1975, Lambers *et al.* 2008). Faster RGR may also maximize the reproductive output in plants with a short life span like *A. altissima*, which is particularly important for ruderals (Grime & Hunt 1975, Chapin 1980, 1988 and Lambers *et al.* 2008) showing this as another advantage for *A. altissima* individuals growing on bare soil. Soil is thermically more stable than gravel, producing less stress on the plants. The smaller pores and colloidal properties of clay and humus in our bared soil test made suffer less evaporation and leaching than gravel. Bare soil presents low leaf number but bigger leaf size allowing



for a larger surface area in which it can take in more fotosynthate and in turn to produce more carbohydrate to contribute to its growing process. Long and broad leaves in bare soil can be explained due to resources disposition because, once leaves begin to produce meristems these grow longer and produce larger leaves. In contrast, gravel provides limited resources such as pulses and over time, brief periods of supplies to help the start of leaves production. Then the rapidly depleting resources allows for less time in which leaves have top grow, a new development aid now pulse of new meristems. At this respect Lambers *et al.* (2008) wrote: Number of leaves and growth of the leaf are affected by disposition of nutrient resource, light, water disposition and plant genetic factor. A close relationship between light interception and yield has been demonstrated for a large variety of plant species (Monteith 1977), including trees (Cannell *et al.* 1988; Linder 1985). For example, it follows that factors influencing leaf area development and the conversion efficiency of intercepted light into biomass are critical for crop production,

#### **4.4.1.2.3 Root effect**

The faster roots elongation in bare soil compared with gravel also confirm substrate with high nutrient disposition are able to contribute to the development and proliferation of *A. altissima*. In soil, water disposition increased top and root (Keever & Cobb 1984). In addition, soil textures contribute greatly to determine root growth, due to the factors like the relative amounts of sand, silt, and clay found in the soil, in turn then affecting the ability of soils to retain both water and nutrients (Lugo *et al.* 1978, Casper &

Jackson 1997, Whalley *et al.* 1998, Riofrio & Wittmeyer 2000, Bernard *et al.* 2005, Jones & Jacobsen 2005). Soils are thermically more stable than gravel producing less stress to the plants roots (Gill *et al.* 2000, Tanner *et al.* 1998).

#### **4.4.2 Intra-specific competition effect**

Germination, RGR based on plant length increased with seed density, all other variables had a contrary effect depend on the substrate.

##### **4.4.2.1 Effect of increased density on *A. altissima* individuals**

RGR based on dry weight, root length, stem basal diameter, leaf number and superficial foliar area decrease with seed density in bare soil and in gravel despite the limited availability of nutrients, the effect is contrary. Casper & Jackson (1997) suggested that soil nutrient levels determining competitive outcome, and according to Wang *et al.* (2005) individuals high density caused growth inhibition as indicated by declines in height, leaf area, and biomass of stems, leaves and roots.

##### **4.4.2.2 Effect of increased density on the different parts of the plant**

###### **4.4.2.2.1 Seeds germination**

Ecologically speaking, the inhibition of *A. altissima* germination by grasses is a mechanism of inter-specific competition. Numerous experimental studies have shown that the survival and growth of an individual plant may be

strongly influenced by competition with its neighbours (eg. Noble 1980, Connel 1983, Mc Murtrie & Wolf 1983, Schoener 1983, Wilson & Keddy 1986a, b, Goldberg 1987, Gurevitch *et al.* 1990, Egerton & Wilson 1993). Competitors were not present on bare soil. Intra-specific competition was impossible for our planted seeds because the germination of seeds is fuelled by the nutrients coming from the “maternal envelope” each seed holds as a legacy of its mother tree (Lambers *et al.* 2008). Once our seeds germinated, the probabilities of them to compete to their co-specifics increased; as our results suggest.

#### **4.4.2.2.2 Aerial part**

Individual density affects stem broad, leaf numbers, and leaf surface area which decrease when individuals plant numbers increased. Plant elongation and leaf area are favoured with the density in bare soil in contrast to gravel which the response is contrary due to the nutrients disposition. *A. altissima* is highly efficient in photosynthesis and stores large quantities of photosynthate in its stem (Bory & Clair-Maczulajtys 1980, Bourdeau 1958, Bourdeau & Laverick 1958, Marek 1988, McTavish 1988). Hard competition (high seed density) activates a mechanism of elongation of the plant to reach the canopy and get more photosynthate and ensure its survival.

#### **4.4.2.2.3 Root effect**

Plant individuals submitted to competition due to high densities of neighbouring plants may improve their water uptake by growing a deeper

root system (Casper & Jackson 1997). This strategy seems to have occurred to *A. altissima*, especially in gravel where roots grow longer to get away from the neighbours and to reach scarce resources all of this occurring at the expense of lower growth and producing small leaves.

#### **4.4.3 Root shoot ratio:**

Root shoot ratio indicates that *A. altissima* invests more resources in the production of roots which guarantees its establishment in comparison with development of leaves or stem for both factors (treatment and density). Resources are also used to produce more roots in gravel than in bare soil. The shoot has first call on carbohydrates while the roots have first call on N (nutrients) and water: when there is a decrease in carbohydrate supply, the shoot retains a larger proportion of nutritional assimilates than the root, thus increasing the shoot: root ratio; whereas the opposite occurs when mineral nutrients or water supplies are decreased (Thornley 1972, Erickson 1995). How root and shoot interact affect plant growth and hold implications for the composition of successional vegetation, especially for pioneer species like *A. altissima* (Casper & Jackson 1995).

Bare soil with highest individual density is where the root stem ratio is higher, indicating higher roots which perhaps more easily reach the resources in soil. The same occurs in the case of gravel where it ensures the survival of the plant as this is capable of meeting the existing and limited resources available in the gravel; the plant uses the few available resources to produce

deeper roots, which leaves it without any resources to invest in secondary growth (Lambers *et al.* 2008).

## 4.5 Conclusions

Grasses out-compete *Ailanthus altissima* by means of suppressing the germination of *A. altissima* seeds.

High densities of *A. altissima* seeds result in intra-specific competition once seeds germinate to become seedlings and saplings; this competition reduces the dry weight of the shoot, stem thickness.

Such competition occurs in the soil (not above ground). The seedlings respond to this competition by investing more biomass to produce roots, potentially reaching soil-resources away of the roots of other *A. altissima* individuals.

The habitats where *A. altissima* is invasive are cities which are places having plenty of bare soil, gravel and cement, and planted grasses (e.g. in cemeteries). From these, bare soils are more able to enhance the germination and earlier stages of vertical growth of the development of *A. altissima*. This is a potential eco-physiological reason explaining the proliferation of *A. altissima* in cities and suggests that the authorities of public and private sectors should focus on bare-soil areas to decide where to place concern and avoid small individuals of *A. altissima* which may in turn become a pest once they are adult trees.

## 4.6 Recommendation

After this study we may recommended for parks, cities and train stations proceed with grass as a ground cover to aid in the prevention and proliferation of *A. altissima*, since it exclusive competence is unable to germinate in presence of grass.

## CHAPTER 5

### **Matrix Model Population as a tool to research and to understand the life cycle of *Ailanthus altissima* in Hesse, Germany**

#### **Summary**

A study was carried out in the summers of 2006 and 2007 in Hesse, Germany with the objective to develop an overview of the actual condition of the population of *Ailanthus altissima* (Swingle). A demographic matrix model was constructed to explore the local population dynamics of this invasive species showing its life history and its invasive success under different conditions such dryness, poor soil nutrient, and pollution. The focus of the study was *A. altissima*, a light-dependent tree with the ability to constitute a long-living seedling bank under unfavourable conditions as well as to re-sprout vigorously once it has been cut down. The dynamics of two *Ailanthus altissima* populations were investigated, one is located in the city centre of Frankfurt am Main (P1) and the other was in the city's outskirts (P2). The model shows that without any control, *Ailanthus altissima* population in outskirt grows considerably every year. The population growth arises mainly from the young tree stage in which *A. altissima* produces a lot of seeds with high possibility to germinate. Population growth rate is also influenced by the high survival percentage in the early life stages up to 10 cm dbh. There are slight growth rate differences between both populations, having the outskirts the highest due to the high survival percentage and seed production and its consequent high germination percentage.

## 5.1 Introduction

Demographic matrix models have become an increasingly important tool for assessing how different impacts and management strategies affect the population dynamics and persistence of species (Schemske *et al.* 1994, Brigham & Thomson 2005). For example, matrixes are used to explore the effects of different harvest frequencies on plant populations (Nantel *et al.* 1996, Maschinski *et al.* 1997, Thomson 2005). The application of demographic modelling to resolve ecological and management problems of invasive plants is also on the rise (Shea & Kelly 1998, McEvoy & Coombs 1999, Parker 2000).

With elasticity analysis, matrix models can be used not only to assess changes in population growth and persistence, but are also used to evaluate which underlying differences in demographic rates and life-history stages are more important in generating those changes. Literature about applied approaches have answered the questions about how the efforts of the management of species could be targeted on particular life-history stages (Crouse *et al.* 1987) and, similarly, which demographic transitions of invasive species have the greatest influence on population growth and contribute most to biocontrol strategies (Shea & Kelly 1998, McEvoy & Coombs 1999). Unfortunately, these publications deal mostly with rare species than with invasive species.

Perturbation analysis of matrix models is a promising new addition to the population ecologist's toolbox. Elasticity analysis allows the estimation and



comparison of the effects on changes in survival, growth, or reproduction of particular life stages, as well as the proportional contribution of different aspects of the life cycle to population growth rate (Heppell *et al.* 2000). *A. altissima* is an invasive tree species introduced in urban environments where its roots break railways and cement structures (Kramer 1995). Its results in millionare lossess of money (Lezcano-Caceres & Gerold 2009), but its population dynamics remains poorly understood. Therefore, the objective of this study focused primarily on to understand population's dynamics of *A. altissima* and to identify its key stages in order to recommend options to control this species and thus reduce their expansive power. We assume that the populations are different and we expect that the population in the city centre is bigger than the other one in the outskirt, because of the well documented urban character of *A. altissima* (Sargent 1888, Kowarik & Böcker 1984, Müller 1987; Gutte *et al.* 1987; Kowarik 1992, Kowarik 1995; Kramer 1995, Rank 1997; Wittig 1998, Huebner 2003, Nesterovic & Jovanovic 2003 Corbett & Manchester 2004).

## **5.2 Methods**

### **5.2.1 Study area and Sampling Design**

The study was carried out in Frankfurt am Main, the largest city in Hesse, Germany (pop. 667.598). Frankfurt is located on both sides of the River Main. In Frankfurt, summers are warm and wet with temperatures varying between 14 and 33.6 °C and frequent rains. Winter is quite chilly with

temperatures dropping to  $-7.6^{\circ}\text{C}$ . The average annual temperature is  $10.7^{\circ}\text{C}$  and the average precipitation is to 560 mm per year.

*Ailanthus altissima* populations were surveyed in the summers of 2006 and 2007 in two plots of 300 x 600 m. One plot (P1) was located in the city centre and one (P2) in the outskirts of Frankfurt. Each plot was subdivided in three subplots (300 x 200 m) and within each subplot a total of 200 *A. altissima* individuals were marked and their vegetative shoots were recorded. During the reproductive season (July to October) all plots were surveyed once a week to visually identify all flowering individuals, count their infrutescences and estimate the number of seeds produced per infrutescences. In order to estimate seed numbers, all infrutescences of ten *A. altissima* trees were collected and the number of seeds per inflorescence was counted. The average seed number of the ten trees was calculated and the number of seeds produced by each tree was estimated.

Since 2006, all plots have been censused annually to record plant growth and mortality of the 200 trees sampled, and the emergence of new seedlings (i.e., established plants less than one year old) was recorded.

Additionally, an essay was conducted to determine *A. altissima* germination percentage. For the essay 5 quadrants (1 m<sup>2</sup> each) were established in each subparcel (300 m X 200 m), in total 30 quadrants were studied and 3000 seeds were sown in these quadrants and seed germination was observed weekly for 2 months.

## 5.2.2 Matrix Model construction

In this study the life cycle of *A. altissima* was divided in five stages: C1: small plants: plants not higher than 20 cm and of less than 1 cm dbh C2:small sapling and small shrub1: plants between 1cm dbh and 4.9 cm dbh, C3:large sapling or large shrub2: plants between 5 cm dbh and 9.9 cm dbh. C4: young tree: plants between 10 cm dbh and 19.9 cm dbh and C5: trees, plants larger than 20 cm dbh. (See Fig.2)

Demographic methods, including the construction of a population matrix models are also described in Bruna & Kress (2002) and Bruna (2003).

From one year to the next, plants can grow into larger size classes, remain in the size class, regress into smaller size classes, (e.g. by breakage) or die. One exception to this rule is surviving seedlings, all of which were reclassified as one-shoot plants in the second year. The probability of transition from stages one (i) to a final stage (j) during the interval between initial time ( $t_0$ ) and final time ( $t_1$ ) was estimated as the proportion of plants in stage initial (i) at time  $t_0$  that made the transition to the final stage (j) at time  $t_1$ . For this study  $t_0 = 0$  (2006) and  $t_1 =$  one year (2007).

### 5.2.2.1 Leslie matrix

This matrix is a special matrix used in demography and population biology and it is referred to as a Leslie Matrix after its inventor Sir Paul Leslie (Leslie 1945, 1948).

A Leslie matrix (Fig. 1) contains: a) age-specific fertilities along the first row (F), b) age-specific survival probabilities along the sub diagonal (S), c) age specific growth probabilities along sub diagonal (R) and d) Zeros everywhere else.

Here is a 4 x 4 Leslie matrix.

$$A = \begin{pmatrix} F_1 & F_2 & F_3 & F_w \\ S_1 & R_{12} & 0 & 0 \\ 0 & S_2 & R_{23} & 0 \\ 0 & 0 & S_{w-1} & R_{ij} \end{pmatrix}$$

Figure 1 A population projection matrix.

The elements of the matrix represent mean fertility per individual ( $F_i$ ) for plants in stage class  $i$ , the probability of survival and growth from a given stage to a larger one ( $R_{ij}$ ), the probability of survival and regression to smaller stages ( $S_{ij}$ ), or the probability of surviving and remaining in the same stage from one time interval to the next (i.e., stasis,  $S_i$ ). Zero entries represent transitions that are never observed.

#### 5.2.2.2 Projection matrix

The life cycle of species with stage-structured life histories (Fig. 1) can be summarized in a stage-structured population projection matrix  $A$ , which elements represent stage-specific transition probabilities or fertility rates (Lefkovitch 1965, Caswell 2001). The top row of matrix  $A$  contains the mean per-individual fertility ( $F_i$ ) for plants in stage class  $i$  (Fig. 1). The other entries of the matrix represent the probability of survival and growth from a given stage to a larger one ( $R_i$ ), the probability of survival and regression to smaller stages (i.e., negative growth,  $R_i$ ), or the probability of surviving and remaining in the same stage from one time interval to the next (i.e., stasis,  $S_i$ ). The population can then be projected using the projection equation  $n_{t+1} = A n_t$ ,

where  $n_t$  is a vector with the abundance of individuals in each stage class at time  $t$ . The total population size in year  $t$  is the sum of the entries of  $n_t$  Leslie (1945, 1948).

Population asymptotic properties can be obtained with:  $A \times n^* = \lambda \times n^*$ , where  $n^*$  is the population vector and  $\lambda$  is the population growth rate. Population decreases when  $\lambda < 1$ , the population increases when  $\lambda > 1$  and when  $\lambda = 1$  the population remains constant. Power method was used to obtain  $\lambda$  and  $n^*$  (Caswell 2001, Zuidema & Franco 2001).

#### **5.2.2.3 Sensitivity and Elasticity analysis**

To indicate how change in variables (such as survival rate) in each category affects the demographic indices, matrix sensitivity and elasticity analyses were carried out (Caswell 2001).

Sensitivity refers to the absolute rate of change of  $\lambda_1$  with respect to absolute change in a matrix element.

Sensitivity is absolute change ( $s = \partial \lambda / \partial a_{ij}$ )

Elasticity analysis of matrix projection models examines the effects of proportional changes in demographic transitions (survival, growth, and reproduction parameters) on the asymptotic population growth rate,  $\lambda$ . Because the elasticity of a projection matrix sums to unity, they can be interpreted as the relative contributions of the matrix transitions to  $\lambda$ . Elasticity

is proportional change  $e = (\partial\lambda/\lambda) = s * a_{ij}/\lambda = (\partial a_{ij}/a_{ij})$ . The effect that each parameter, or suite of relevant parameters, has on population growth has been used as an index for evaluating the "importance" of certain life stages or demographic rates for management and research.

A five-stage ( $C_1$  to  $C_5$ ) of *A. altissima* life cycle and their transition probabilities (growth, survival and fertility) in both populations is represented in Fig.2.

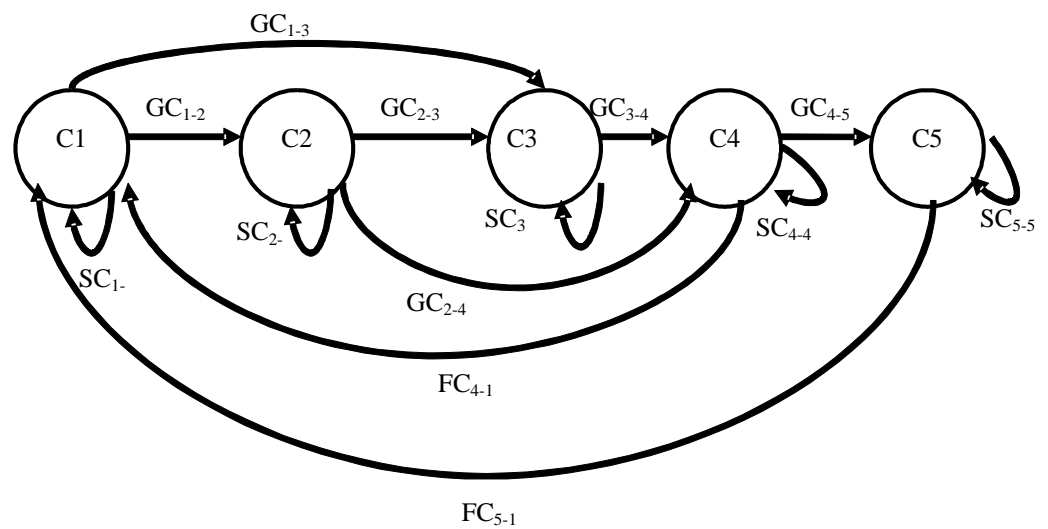


Figure 2 Life-cycle diagrams for *Ailanthus altissima*.

Figure shows the five stages classes considered and all possible transitions between them. G = all individuals which grow to the next group; S = all individuals who survive to the next group, F = fertile individuals that are incorporated into the first stage.

The results were analyzed with Excel program extension PopTools V 2.0. PopTools is a versatile add-in for PC versions of Microsoft Excel (97, 2000 or XP) that facilitates analysis of matrix population models and simulation of stochastic processes.

### 5.3 Results

The original matrix for the plot located in the centre of Frankfurt am Main (P1) showed (Fig. 3) a high survival rates especially in individuals from the third stage (large sapling or large shrub2) to the fifth stage (trees) passing through the stage of young trees (see C<sub>3</sub>, C<sub>4</sub> and C<sub>5</sub>), in addition a large seeds production in young and adult trees (C<sub>4</sub> and C<sub>5</sub>, Fig. 3).

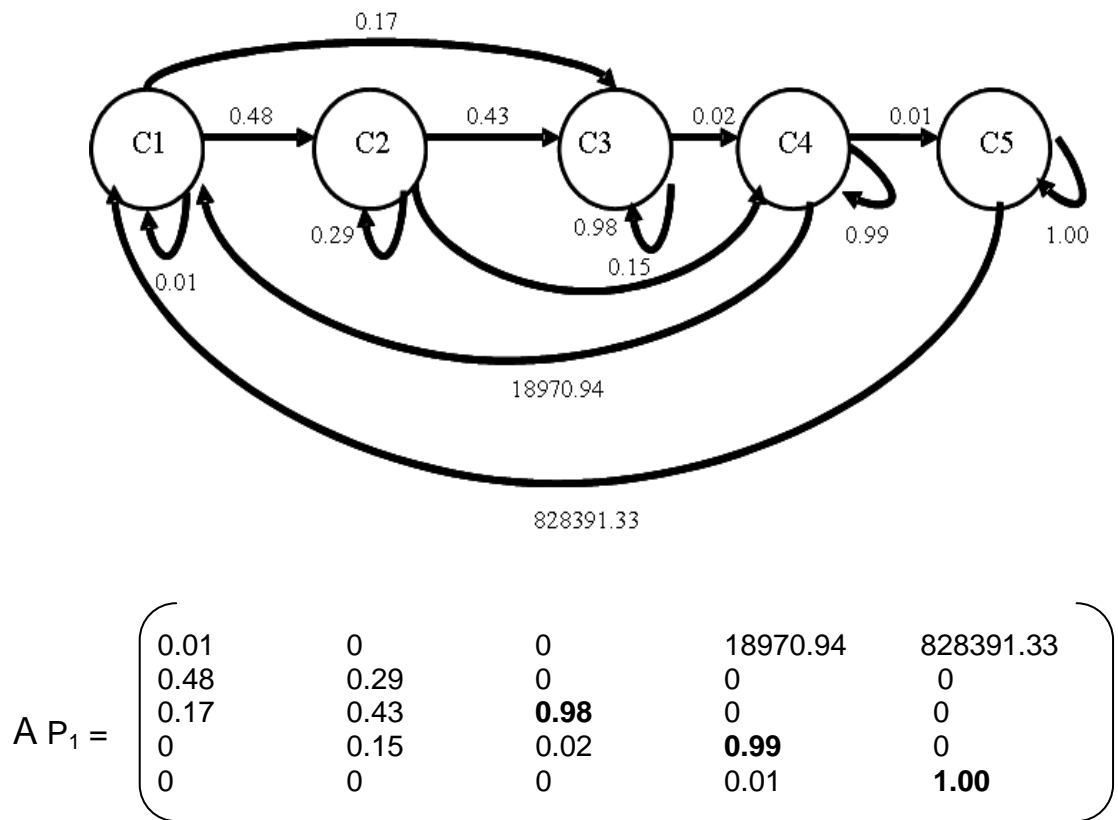


Figure 3 Population projection Leslie matrix of *Ailanthus altissima* in the centre of Frankfurt am Main.

The figure shows the transition of all stages of the population.

The plot located in the outskirts of Frankfurt city (Fig. 4) shows similar matrix results than the centre of Frankfurt plot but the transition rates from the third to the fourth stage (C<sub>3</sub> to C<sub>4</sub>) are not as high as in the plot in the city centre

(Fig. 4). The results also showed that the youngest trees produced more seeds in comparison with the younger trees in the parcel in centre.

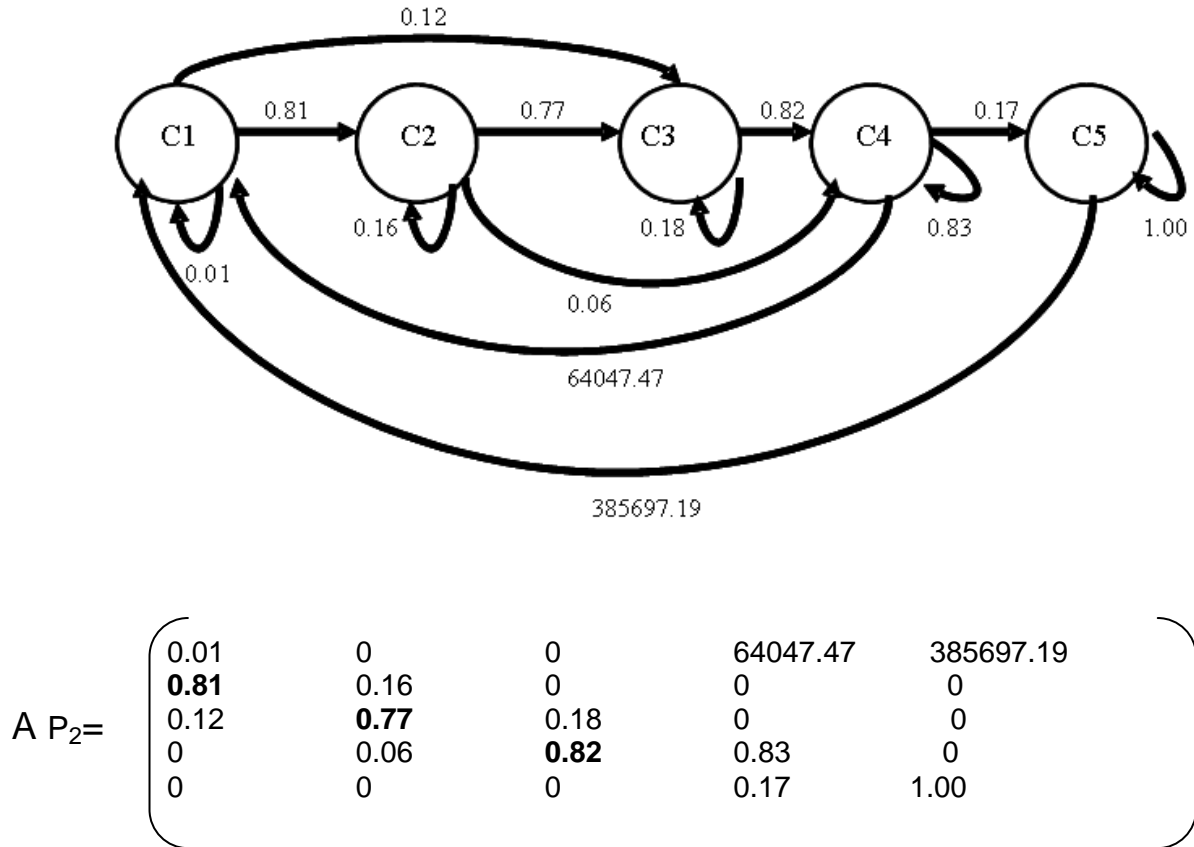


Figure 4 Population projection Leslie matrix with all possible transition for the population of *Ailanthus altissima* outskirts of Frankfurt am Main.

*Ailanthus altissima* population increases each year  $\lambda > 1$  for both plots, P1  $\lambda = 11.9$  and P2  $\lambda = 23.12$  but young trees population in the outskirts produces more seed compared to population located in plot of the centre of Frankfurt.

Germination percentage in all quadrants present a mean of  $55 \pm 7\%$ , this values were roughly similar to observed in the study of *A. altissima* under different substrate type and seed densities (Lezcano-Caceres in prep).



Figure 5 shows the abundance of individuals in two years (2006 – 2007). The value of the first stage at initial time ( $C_{1t_0}$ ) is the result of the number of seeds produced and multiplied by the germination percent (Lezcano unpublished data). In most cases an increase in the number of individuals was observed in the second year since a high survival and low mortality percentages was assumed in the early tree stages of plant growth for both surveyed plots (Fig. 5a and Fig. 5b).

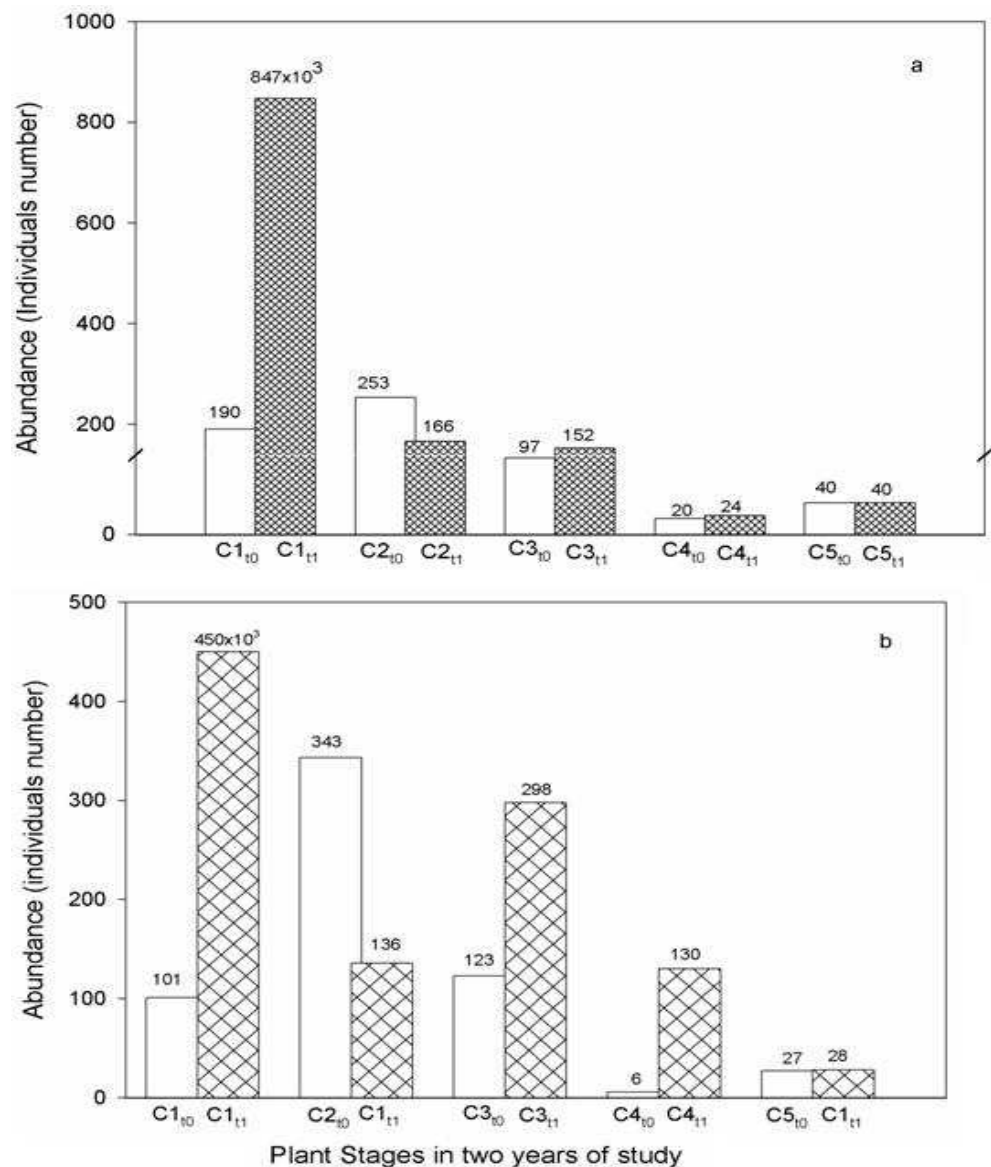


Figure 5 Abundance of *Ailanthus altissima* in all stages studied along two year research. a) Plot in the centre of Frankfurt am Main (P1), b) Plot in the outskirts of Frankfurt am Main (P2). Nomenclature  $C_1$  to  $C_5$  refers to the five growing stages;  $t_0$  refers to the initial time and  $t_1$  refers to the time after one year of study.

### 5.3.1 Sensitivity and elasticity

The sensitivity matrix suggests that transitions from younger to older trees ( $C_2$  to  $C_4$ ,  $C_3$  to  $C_4$ ,  $C_4$  to  $C_5$ ,) and shrub1 recruitment ( $C_1$  to  $C_2$ ) have the highest absolute influence on tree growth rate. Transitions in the following stage ( $C_1$  to  $C_2$ ,  $C_1$  to  $C_3$ ,  $C_2$  to  $C_3$ ,) are also important (Fig. 6).

$$S = \begin{pmatrix} 0.32 & 0 & 0 & 2.0 \cdot 10^{-4} & 1.75 \cdot 10^{-7} \\ 7.44 & 0.31 & 0 & 0 & 0 \\ 1.05 & 0.04 & 0.02 & 0 & 0 \\ 0 & 23.70 & 9.86 & 0.34 & 0 \\ 0 & 0 & 0 & 14.47 & 0.01 \end{pmatrix}$$

Figure 6 Sensitivity matrix test for the population of *Ailanthus altissima* in Frankfurt am Main city centre, Germany.

The elasticity analysis suggests that plant growth in the first and third stages ( $C_1$  to  $C_2$  +  $C_2$  to  $C_4$ ) has the highest influence (0.60) on the proportional variation of the growth rate followed by young trees fecundity (i.e. age at first reproduction  $C_4$  to  $C_1$ ) Fig. 7.

$$E = \begin{pmatrix} 3.0 \cdot 10^{-4} & 0 & 0 & \mathbf{0.30} & 0.01 \\ \mathbf{0.30} & 0.01 & 0 & 0 & 0 \\ 0.02 & 1.6 \cdot 10^{-3} & 1.5 \cdot 10^{-3} & 0 & 0 \\ 0 & \mathbf{0.30} & 0.02 & 0.03 & 0 \\ 0 & 0 & 0 & 0.01 & 1.0 \cdot 10^{-3} \end{pmatrix}$$

Figure 7 Elasticity matrix test for the population of *Ailanthus altissima* in Frankfurt am Main city centre, Germany.

The sensitivity test of the outskirts Frankfurt plot shows the greatest contribution in the growth rate and that the important value of growth in the young stages ( $C_1$  to  $C_3$ ,  $C_2$  to  $C_4$ ,  $C_3$  to  $C_4$  and  $C_1$  to  $C_2$ ), and survival phases ( $C_3$  to  $C_3$  and  $C_4$  to  $C_4$ ) are also important Fig. 8.

$$S = \begin{pmatrix} 0 & 0 & 0 & 1.0 \text{ e}^{-4} & 8.22 \text{ e}^{-7} \\ 3.66 & 0.13 & 0 & 0 & 0 \\ 34.22 & 1.22 & 0.22 & 0 & 0 \\ 0 & 33.77 & 6.16 & 0.32 & 0 \\ 0 & 0 & 0 & 1.86 & 0.01 \end{pmatrix}$$

Figure 8 Sensitivity matrix test for the population of *Ailanthus altissima* in the outskirts of Frankfurt.

The elasticity matrix suggests young trees fertility ( $C_4$  to  $C_1$ ) has the highest proportional influence on the growth rate. It also suggests that, growth of juvenile plant stages ( $C_3$  to  $C_4 + C_1$  to  $C_3 + C_1$  to  $C_2 = 0.53$ ) is also important for the  $\lambda$  increase Fig. 9.

$$E = \begin{pmatrix} 0 & 0 & 0 & \mathbf{0.30} & 0.01 \\ \mathbf{0.13} & 9.0 \text{ e}^{-4} & 0 & 0 & 0 \\ \mathbf{0.18} & 0.04 & 1.8 \text{ e}^{-3} & 0 & 0 \\ 0 & 0.09 & \mathbf{0.22} & 0.01 & 0 \\ 0 & 0 & 0 & 0.01 & 6.0 \text{ e}^{-4} \end{pmatrix}$$

Figure 9 Elasticity matrix test for the population of *Ailanthus altissima* in the outskirts of Frankfurt am Main, Germany.

Growth followed by fertility are the most important factors to consider regarding tree vital rate components considered in *A. altissima* populations plots (Fig.10).

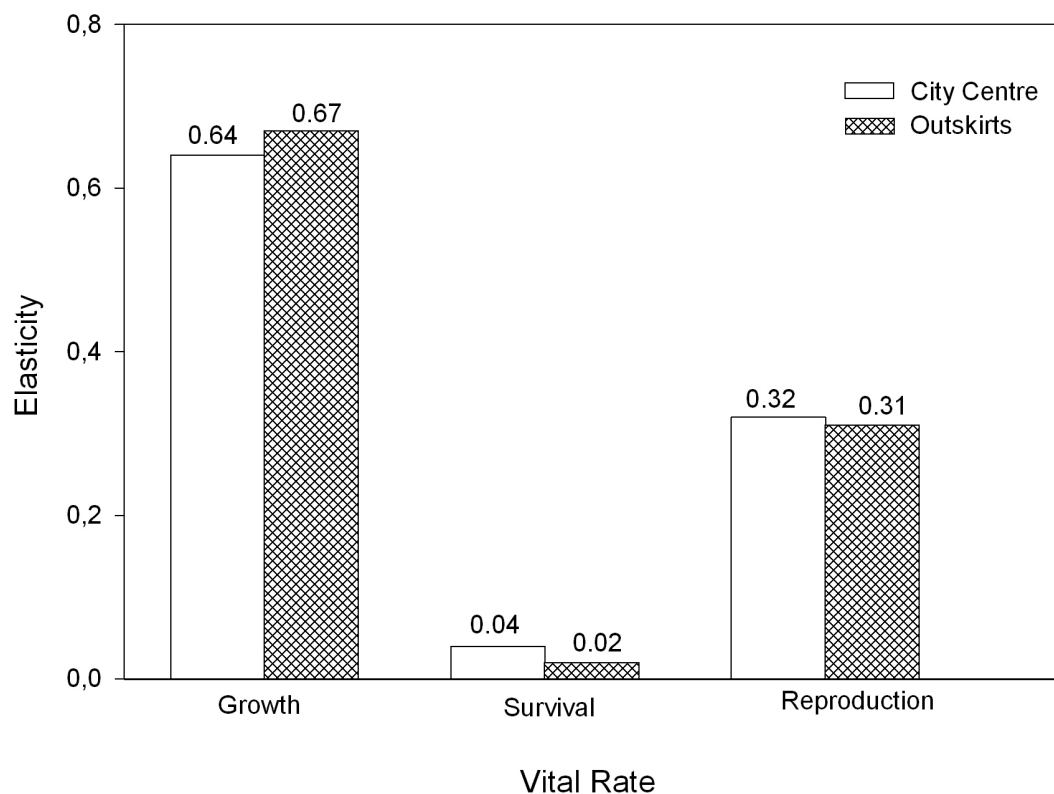


Figure 10. Elasticity values in each vital rate regarding the population of *Ailanthus altissima* in the city Frankfurt am Main (P1), and its outskirts (P2), Germany.

## 5.4 Discussion

This research was based on the fundamental assumption that both populations are different and that the population in centre of Frankfurt am Main, Germany is bigger than the outskirt population. The results of this demographic study showed that both populations have high growth rates caused by the high seeds production, high recruitment rate and high survivor rate. These characteristics contribute to explain conclusions from ecophysiological studies referring to the invasive power of *A. altissima* near

to urban areas, especially in cities (Miller *et al.* 1965, Müller 1987, Kowarik 1992, Kramer 1995, Wittig 1998, Penn 1999, Huebner 2003, Howard 2004, Fergus 2005), and recently in forest (Kowarik 1995, Knapp & Canham 2000).

The main problem regarding the growth rate of this population is the combination of a reflected in a high recruitment from trees ( $C_5$ ) and young trees ( $C_4$ ) to small plants, the high germination percentage of *A. altissima* and a high survivor rate special in two older stages of the plant (young trees -  $C_4$ - and trees - $C_5$  -). Once *A. altissima* seeds are in contact with light they increase their germination percentage (Kowarik & Säumel 2006). *A. altissima* is considered a light-demanding pioneer species that usually invades disturbed areas and grows very fast under light conditions (Kowarik 1995; Knapp & Canham 2000). Although it can live in a low-light understory for at least 19 years (Kowarik 1995), it is primarily considered a gap-obligate species in a mature forest and has been able to successfully colonize a gap in an old-growth hemlock forest in New York (Knapp & Canham 2000).

For wind dispersed (anemochorous) seeds like *A. altissima*, biological factors include the height of seed release, fecundity, and geometry of source plants (van der Pijl 1982, Tackenberg 2003), together with seed size, mass, shape, terminal velocity, and the strength of the physical connection to the infructescence (Augspurger & Franson 1987, Matlack 1987, Greene & Johnson 1992). Physical factors include local topography, the intensity and direction of dispersal events, landscape structure, and the structure of the environment within which dispersal occurs (Sharpe & Fields 1982, Nathan 2001, With 2002). Environmental structure, defined as the spatial

arrangement of physical objects in a habitat (McCoy & Bell 1991), can play an important role in the seed dispersal process because structure influences local wind velocity and direction (Coutts & Grace 1995), two factors that in turn affect the seed rain at various distances from their source, laying the template for recruitment (Levin *et al.* 2003). Despite its apparent importance, little is known about the relationship between environmental structure and seed dispersal in contrasting habitats. Environmental structure is ecologically important not only because it influences how far a seed travels but also because it determines the fate of the seed after its arrival (Chambers & MacMahon 1994). Understanding variability in seed dispersal patterns within and between habitats characterized by differences in structure allows general predictions of an invasive species' rate of spread in landscapes composed of several different suitable habitat types.

Furthermore, *A. altissima* in contact with water increase significantly influenced on the start, duration and rate of germination (Kowarik & Säumel, 2006). Genetic factor seem haven't influence its successful germination, whereas the proportion of germinated seeds differed not among maternal source trees (Kota *et al.* 2007).

In addition, despite the fact that, in the city centre, *A. altissima* early stages are controlled by cutting and removal, new recruitments are responsible for the rapid population growth found. During the first phases the plant can grow very fast. With a rapid stem elongation, *Ailanthus* is believed to be the fastest-growing tree in North America (Knapp & Canham 2000; Howard 2004) and Britain (Mabberley 1997). The fast grow of the new individuals

especially during the first year make the removal efforts by applied by garner difficult, because, once individuals reach more than 2 to 3 meters ( $C_2 - C_3$ ) high they are very difficult to control and eradicate. These assertions can be strengthened through studies by Adamik & Brauns (1957), DenUyl (1962), Hu (1979), Bory & Clair-Maczulajtys (1980), Miller (1990), Hobbs & Huenneke (1992). Height increment as well as diameter growth are highest in trees between 5 and 10 years old and continue under favourable conditions to an age of 10–20 years, and then begin decreasing (Speranzini 1937).

As expected, elasticity analysis showed that fertility was the most important factor regarding the growth rate. However, growth itself also showed to be also very important. Therefore, there is a need to consider these two parameters in monitoring and controlling populations of *A. altissima*, pruning is needed especially in plant stage  $C_4$  and  $C_5$  before they start to produce flower.

With respect to the plot located in within Frankfurt compared to the plot located outside the city we thought that the first mentioned population should show small growth and reproduction rates due the means of control. But, in this case, control strategies do not seem to be a crucial factor regarding the growth rate from *A. altissima* as both populations show a high growth rate and similar values for all three vital rates analysed.

## 5.5 Conclusion

Populations of *A. altissima* increase every year, as demonstrated by lambda ( $\lambda > 1$ ) values obtained for both populations. Despite controls methods carried out to control *A. altissima* plants, annually seed number produced as well as higher tree survival rates are the main factors contributing to *A. altissima* population growth.

Based on the results obtained in this study, we can point out that the two problematic stages regarding the control of *A. altissima* population are the adult individuals ( $C_5$ ) that produce large numbers of seeds and high survival rate ( $C_3$ ,  $C_4$ ,  $C_5$ ). This implies that cutting of adult individuals ( $C_5$ ), especially at the reproduction time by eliminating branches with greatest seeds number can brake the cycle and control the population.



## CHAPTER 6

### **The costs of invasion control measures subtropical *Ailanthus altissima* in Hesse.**

#### **Summary**

Global commerce moves plants from their natural places to others where many of them become invasive. The subtropical tree *A. altissima* is invasive in temperate zones because global change makes the latter warmer. Such proliferation causes root-induced damages to the foundations of buildings, water channels, railroads and pavements; also the pollen of *A. altissima* is allergenic to people. We interviewed to top-officers of parks, the railway company and health ministry in the state of Hesse (Germany) to assess how much the different strategies to control *A. altissima* for the whole state cost. Uncontrolled damages totalized 5Mi €/ y. The most expensive control strategy combines fire and steam, costing 295718 €/ha; the cheapest one was poisoning 6400€/ha. None of the control techniques reduces plant reproduction so we suggest pruning *A. altissima* in June and July, when it starts flowering in order to reduce populations to save money for further years.

#### **6.1 Introduction**

Transportation for commercial proposes made many plants like *A. altissima* (Mill. Swingle Simaroubaceae) able to leave their natural habitats, colonize others and proliferate more than native plants. Human colonization and commerce increased the scale and impact of such invasions. Introduced

species often have no natural enemies in their new environments so they spread quickly (Vitousek *et al.* 1996, Mooney & Hobbs 2000, Defra 2003). As a consequence, invasive plants reduce the populations and even extinct other native plants and animals (e.g. by means of competition or toxicity), and affect the functions of ecosystems and habitats (Munyaradzi & Mohamed-Katerere 2003, Pyšek *et al.* 2004).

*Ailanthus altissima* (known as Tree of Heaven) is a pioneer tree, native to eastern China (Hu 1979, Hoshovsky 1988, Kramer 1995, Kowarik & Säumel 2007), introduced in Europe in 1751. Currently, *A. altissima* is present in more than 30 countries, being invasive in disturbed, urban areas of Europe – including Germany. After the Second World War, *A. altissima* was used in Germany for public gardens and then spread across Europe (Kowarik 1983, Kowarik & Böcker 1984, Hoshovsky 1988, Knapp & Canaham 2000). Now it damages buildings foundations, streets, sidewalks, water channels and railways so private and government agencies invest millions of Euros to control this species. This study assessed: (a) what control techniques are used against *A. altissima* proliferation in the State of Hesse, Germany, and (b) how much these controls cost in addition to the costs of medical treatment for allergies.

## **6.2 Material and Method**

During the winters of 2005 and 2007, we interviewed 10 top-directors of parks, three top-managers of the German Railway Company (Deutsche Bahn –DB) and two top-officers of the health authorities. They were asked for the prices of management, equipments, salaries and costs for the control of *A.*

*altissima* in the whole state of Hesse. Printed information supplied by DB ([www.db.de/sustainability-report](http://www.db.de/sustainability-report)) and on the costs of anti-allergic treatment was consulted as well.

## 6.3 Results and Discussion

Uncontrolled spread of *A. altissima* species costs up to 5 Mi €/y in Hesse. About 18% of investments in monitoring by the DB are devoted only to such species. In 2007 about 61 % of the 64,000 Km of track were treated with an herbicide specifically developed for this use. The “killing by heating” method combined to steam control costs was the most expensive practice (295718 €/ha) whereas poisoning was the cheapest (6400€/ha). Allergies caused by the pollen of *A. altissima* costed 1.5 Mi € /year.

In Hesse, physical, chemical and thermal methods of control are the main methods used to control this species.

### Physical control:

The cost of controlling *A. altissima* can be seen in Table 1.

Table 1 Cost analysis of physical methods to control *Ailanthus altissima* in Hesse (Germany).

Management approach type of Control	Labor cost/h	Equipment cost	Time (h) required to treat a 1 ha	Total cost of management of 1 ha (€)	Total cost in 5 year (€)	Total cost in 10 years (€)
Physical						
Removed (total)	20-40	500-1000	114	5560.00	23800.00	46600.00
Cutting	20-40	25000-30000	80	33200.00	46000.00	62000.00
<b>Total</b>				<b>38700.00</b>	<b>69800.00</b>	<b>108600.00</b>

Although the physical control is easy to implement and not very expensive, it causes a series of problems that need to be considered. As with most trees, the mowing of seedlings is quite effective. Girdling is effective for killing the tops, but the main problem with this control type is that the plants will sprout again. Many authors pointed out that cutting *Ailanthus* is the only method that will not kill the tree, but will promote it to re-sprout vigorously instead (Yancey 2007). The only reported effective mechanical control of *A. altissima* is hand pulling young seedlings before they have a chance to produce a large root system (Pannill 1995, 2002; TN-EPPC 1996). For an efficient control it is therefore necessary to combine this control method with others.



Figure 1 Physical treatment in the management of *Ailanthus altissima* a & b Mechanical methods, c, thermal method.

### Thermal control

Plant control with fire and steam is commonly used by the Deutsche Bahn to reduce plant populations near railway tracks. The costs of this control type can be seen in Table 2.

Table 2 Cost analysis of thermal methods to control *Ailanthus altissima* invasion in Hesse (Germany).

Management approach type of Control	Labor cost/h	Equipment cost	Time required to treat a 1 ha area (h)	Total cost of management of 1 ha (€)	Total cost in 5 year (€)	Total cost in 10 years (€)
Thermal						
Fire	20-40	(50-125000)	40-60	127400.00	137000.00	149000.00
Damps	20-40		80-100	129000.00	145000.00	165000.00
<b>Total</b>				<b>256400.00</b>	<b>282000.00</b>	<b>314000.00</b>

Studies on *Ailanthus*'s response to fire are lacking, though inferences are possible based on known attributes and anecdotal accounts.

*Ailanthus altissima* sprouts from the roots, root crown, and/or bole after aboveground or top damages (Hull & Scott 1982, Kentucky Exotic Pest Plant Council 2001, Miller 1990, Southeast Exotic Pest Plant Council, Tennessee Chapter 2001) and anecdotal accounts Lepart (1991), suggest that *A. altissima* sprouts vigorously after it has been burnt. Therefore it has been stated (Virginia Department of Conservation and Recreation, Division of Natural Heritage. 2003) that *A. altissima* trees highly persist in some areas despite burning. *A. altissima* would probably succeed in the competition for light and nutrients against native woody species right after fires have occurred.

### **Chemical control**

Chemical controls are the cheapest control methods, despite the use of agrochemicals in Europe, it is strictly limited to small doses, Glyphosate is effective both as a spray and as a stump treatment, but many repeated applications may be necessary to kill individuals of this species (Sterrett *et al.* 1971).

It seems that chemical control is the most cost effective method to *A. altissima* apart that it can be applied to the leaves, to the basal bark, cut stump, or hack and squirt treatment. It is important to consider that despite it is relatively easy to kill the above ground portion of *Ailanthus* trees; it is

necessary to kill or seriously damage the tree root system to prevent or limit stump sprouting and/or root suckering (Swearingen & Pannill 2003).

Table 3 Cost analysis for chemical methods to control *Ailanthus altissima* invasion in Hesse (Germany).

Management approach type of Control	Labor cost/h	Equipment cost	Time required to treat a 1 ha area (h)	Total cost of management of 1 ha (€)	Total cost in 5 year (€)	Total cost in 10 years (€)
Glyphosate	20-40	500-5000	5-10	1409.00 (+5000 eq) 6409.00	3045.00 (+5000 eq) 8045.00	5090.00 (+5000 eq) 1090.00
Garlon 4	20-40	500-5000	5-10	1491.00 (+5000 eq) 6491.00	3455.00 (+5000 eq) 8455.00	5910.00 (+5000 eq) 5910.00
<b>Total</b>				<b>6500.00</b>	<b>9500.00</b>	<b>11000.00</b>

Studies conducted in USA (Burch & Zedaker 2003) show that *A. altissima* treated with herbicides was more efficient in controlling and killing *A. altissima* trees when compared to manually cutting the stems. Manual cutting averaged 1.6 new stump sprouts per stem, while none of the chemical treatments produced any stump sprouts and 21% of cut stump trees failed to re-sprout, compared to 79% or greater mortality using chemical control methods.

### Biological methods

Although this type of control was not reported in the interviews conducted, we note its existence and its costs based on a literature review were calculated.

A potential biological control for *Ailanthus* may lie in several fungal pathogens, (*Verticillium dahliae* and *Fusarium oxysporum*) that have been isolated from dead and dying *Ailanthus* trees in New York and in southern and western Virginia (Miller 1990, Riffle & Peterson 1986).

The estimated costs for the biological control using fungi species is shown in

Table 4.

Table 4 Cost analysis of biological methods to control *Ailanthus altissima* in Hesse (Germany). \* The value of the strains ranges between 30 and 58 € for non profit making institution and 48 and 85 € for other institutions (additional shipping 25 € in Germany and 60€ European and other countries).

Management approach type of Control	Labor cost/h	Equipment cost	Time required to treat a 1 ha area (h)	Total cost of management of 1 ha (€)	Total cost in 5 year (€)	Total cost in 10 years (€) BNM
Biological						
Entomo Fungi <i>Fusarium oxysporum</i> * <i>Fusarium latritium</i> * Price List Jan. 2007	No data 30€ 38€	No data 30000 €	No data 8-12	No information 240- 360 (+30000 eq) <b>30360€</b>	No information 1200- 1800 (+30000 eq) <b>31800€</b>	No information 2400-3600 (+30000 eq) <b>33600€</b>
<i>Verticillium dahliae</i> *	30€ 40€	30000 €	8-15	240-600 (+30000 eq) <b>30600€</b>	1200 - 3000 (+30000 eq) <b>33000€</b>	2400-6000 (+30000 eq) <b>36000€</b>
<b>Total</b>				<b>30600€</b>	<b>33000€</b>	<b>36000€</b>

Although it has been reported that *Verticillium* can effectively kill the plant, its use would be inappropriate as a biocontrol due to its long life span in soils. This can infect the native vegetation and cause additional problems.

Other major problem occurring when using biological methods is their long time that passes before a tree dies.

The last point of this study includes the impact of this invasive species on human health, this kind of costs were calculated indirectly from interviews at the allergy centre, because some allergies can be caused by more as one plant species.

Table 5 Estimated annual costs incurred by *Ailanthus altissima* in Hesse (Germany).

	Incurring Costs	Upper and Lower Limits	Remarks
allergic asthma <sup>&amp;</sup>	27500000	20500000 to 37500000	annual direct and indirect costs
allergic rhinitis (hay fever) <sup>&amp;</sup>	3800000	2500000 to 10800000	annual direct and indirect costs
eradication costs	296447.71	250000 to 300000	annual direct and indirect costs
<b>Total</b>	<b>31596447.71</b>	<b>232500000 to 48600000</b>	

\*\*\* Data obtained from national and international medical sources. Cost in €.

*Ailanthus altissima* has some good features; too, the wood is often used in China for lumber, fuel wood and other products. In the U.S. it is occasionally used for low-grade lumber, pulpwood and fuel wood. The honey produced in Europe with its flower is a good quality product; additionally the toxin produced in the bark and leaves of *A. altissima* is being studied as a possible source for a natural herbicide. [http://zipcodezoo.com/Plants/A/Ailanthus altissima.asp](http://zipcodezoo.com/Plants/A/Ailanthus_altissima.asp) Dic. 2007.

Results shown here are consistent to studies showing economic damages by invasive species ranging from 8 Mi- to 16 Bi €/y (U.S. Congr. Off. Technol. Assess. 1993, Pimentel *et al.* 2000, Pimentel 2002, World Bank 2002, UFZ 2002, Cock 2003, Andreu & Vilá 2007). *A. altissima* may also alter the species composition of plants and animals (e.g. pollinators). As well, it may alter ecosystem functions like nitrogen and carbon cycling; all these have been demonstrated for other invasive trees in Europe (Williamson 1996, Wilcove *et al.* 1998, Parker *et al.* 1999, Sala *et al.* 2000, Stein *et al.* 2000, Marchante *et al.* 2001). In spite of the well known damages and costs to control *A. altissima* we found that none of the very expensive control strategies practiced in Hesse avoids *A. altissima* populations to recover. In



concrete, new seeds and seedlings are always produced and remain able to colonize new areas. Besides throwing small plants to avoid them to become adults, we propose that managers prune *A. altissima* adult individuals in June and July –when they start to flower. Combined both practices and avoid adults to produce offspring, reduce rapidly the size of the populations, save money for the following years, and are applicable to all places invaded by *A. altissima*.

## 6.4 Conclusion

In managing *Ailanthus altissima* populations by physical methods despite its simplicity and easy applicability have proved not to be a cost effective alternative for chemical methods. However, in Europe this type of control is highly restricted to prevent pollution and the damage of native diversity. Although biological control costs are relatively low, this method should be well evaluated since its application frequency and effectiveness has not yet been fully evaluated.

## 6.5 Recommendation

Because of its invasive power, management and control of *A. altissima* is rather complicated and expensive. To give recommendations for the best ways of control this species and the costs it causes, among other things it is necessary to consider several factors as: affected areas, required personnel, protection of native diversity, effectiveness of the method to use, investment interest of agencies involved in this control.

## CHAPTER 7

### 7.1 General discussion

The study of *Ailanthus altissima* in the urban-rural gradient and in stations in Hesse has enabled us to understand how the species is distributed in the Federal State of Hesse, Germany where the species is most commonly found in urban areas and train stations. Within Hesse, there is a reduction of the occurrence and abundance of *A. altissima* towards the north (e.g. more individuals in Frankfurt than in Kassel). This northern region is closer to the upper boundary of the limit distribution of *A. altissima* in Europe. Other studies indicate that this varies with the number of sunny days and temperatures below 15 °C in summer (Kowarik & Böcker 1984, Kramer 1995); this is consistent to our results. For example in the north of Hesse is the city of Kassel with only 3 *A. altissima* individuals even though the city has a higher population density –more urban- (8.5 °C with 1368 sunshine hours per year) and Darmstadt south with 119 *A. altissima* individuals (10 °C and 1686 sunshine hours annually, DWD 2008). To our knowledge -however, experimental studies testing the relative importance of both number of sunny days and temperature variation on the fitness of *A. altissima* remain undone.

*A. altissima* has proven to be more successful in urban- than in rural areas that leverages open spaces produced by anthropogenic disturbances, (Rabe & Bassuk 1984, Pan & Bassuk 1985, Graves *et al.* 1989, Miller 1990, Pickett & Facelli 1991, Lodge 1993, Kowarik 1995, Knapp & Canham 2000 and Huebener 2003). This reaffirms our results that the species is distributed along an urban-rural gradient, with more individuals in crowded cities,

through relatively medium-sized populations of *A. altissima* in small towns, to a lower frequency and abundance in areas of natural vegetation and forest. Other studies have found similar patterns (Kowarik 1995, Kramer 1995) Knapp & Canahan 2000).

Responses of *A. altissima* at microhabitat level within cities. There, areas with higher human population densities presented more *A. altissima* individuals. This may be due to at least two factors: (a) infrastructure contributes to increased the temperatures favouring the establishment compared to green areas as parks, cemeteries and to industrial areas, (b) control measures applied are more frequent, strict and coordinated in green areas than in private gardens in the neighbourhoods.

How *A. altissima* does responds effectively to the microhabitats of most populous cities? The species is pioneer and able to grow in different substrate types (Feret 1985, Agro Forestry Tree Database <http://www.worldagroforestrycentre.org/Sea/Products/AFDbases/AF/asp/SpeciesInfo.asp?SPID=1786>) and dry environments (Adamik & Brauns 1957, Bory & Dubroca But see 1981as well as in highly polluted sites (Plass 1975, Jovanovic *et al.* 1998, 2003 Nestorović & Jovanović). *A. altissima* also produces many seeds (Hu 1979, Bory and Clair-Maczulajtys 1980, Hoshosvki 1986) and its vegetative reproduction is vigorous (Miller 1990, Bory *et al.* 1991, Singh *et al.* 1992, Kowarik & Säumel 2007). *A. altissima* efficiently uses the available resources of its habitat by performing high germination rates (58-65%) and growth rates (1.5-to 2 m.y<sup>-1</sup>), and a high survival rate after reaching 2 m in height. If resources are abundant, the

individuals grow in a rapid and stable fashion, but under limited resources the plant invests in roots production to reach deep resources in soil and reduces growth (Chapter 4). *A. altissima* also produces allelopathic chemicals which inhibit the germination and growth of other, surrounding species (Mergen 1959, Heisey 1990, 1996, Lawrence *et al.* 1991). However when competitors like grasses are previously established, the germination and growth of *A. altissima* decrease (Chapter 4), which helps to explain the lower abundance of the species in cemeteries and parks. The same may be applicable in forested areas where the presence of other established tree species decreases the chances of finding *A. altissima* individuals as observed in studies done in the Taunus region (Chapter 2). There, only eight young individuals of *A. altissima* have been found (Uebeler *et al.* 2008).

There are studies showing that *A. altissima* is able to prosper on pavement (Feret 1985, Pan & Bassuk 1985). Our experiments show that it is not necessarily the case: the species had poor germination and growth on gravel compared to bare soil. Rural areas have more grass compared to urban areas; our results show that this condition limited germination and growth of *A. altissima*.

On another hand, our population dynamics study showed that *A. altissima* ten-folds its population size yearly. Besides our study of the economic costs of control, this gives just a picture of the impact that this species is causing in Germany.

We believe that our study case in Hesse can apply to Germany and even to other countries of the European Union. In fact, the species is present in major cities like Lisbon, Barcelona, Rome, Athens, Berlin and Prague (H.L. Lezcano-Cáceres, personal observation) which share some characteristics like abundant human populations, infrastructures and traffic with Frankfurt (the main city of our study). It is true that our study was limited to Hesse (for financial reasons and time) and that for large cities our sample size is  $n = 1$  (city of Frankfurt am Main). Nevertheless, according to statistics (Tourismus & Congress GmbH 2009) about 2 million people are moving in the city and its surroundings and this is very similar to other European cities and in the world (e.g. Brussels or Rotterdam) when cities are classified by order of magnitude of the number of people moving using all types of transportation and traffic available. These other cities have also urban-rural gradients similar to our study, green areas and neighbourhoods. We therefore propose that patterns of spatial changes in *A. altissima* abundance in our study can be applied to other parts of the world, particularly in Europe, as the home state of Hesse and Frankfurt are strongly interconnected with other parts of this continent.

The economic interest on *A. altissima* is increasing as noted in this study and as also referred by Kowarik (1983), Adolphi (1995), Facelli & Pickett (1991), Singh *et al.* (1992), Burch & Zedaker (2003), Huebner (2003), Merriam (2003). The public and private sectors spend over 5 million €.  $y^1$  (Lezcano-Cáceres & Gerold 1999). Another indicator can be the investment in the treatment of diseases caused by allergies to pollen and its chemical components (Ballero *et al.* 2003, Derrick & Darley 1994). Allergic asthma

produces direct and indirect costs of 2.6 billion euros annual (Allergy 1997, Wettengel & Volmer 1999, Bachert 2000). Unfortunately, allergies caused by aliens –including *A. altissima* have not been investigated in Germany as a separate category, and cases of allergies have often been confused with allergic reaction to native species too.

### ***Ailanthus altissima* in Hesse: a possible model for understanding and controlling other invasive plants across Europe**

Since the population size of *A. altissima* is larger the larger a city is, since the species has a very high population increase in such cities, and because cars and other vehicles are proposed as seed dispersors, we propose that large cities are reservoirs and sources to expand the populations of *A. altissima* to suburbs, smaller cities and villages.

Moreover, the presence of *A. altissima* on the European continent is an example of the invasive species encouraged by human intervention. We think that his example can be applied to a variety of introduced species in Europe, which proliferated after the Second World War (WWII) and today are found worldwide. We assert this considering some ecological characteristics of other invasive plants respect to *A. altissima* (high seed production, colonization of open areas, rapid dispersion and rapid growth). Kowarik (2003) enlisted 26 plant species invasive in Europe; I modified the table adding the habit of each plant (tree, shrub or herb) and the seed dispersal

mechanism (anemocory=wind dispersed or zoocory=animal dispersed, Table1).

Table 1 Invasive species of urban-industrial habitats, origin, habit, dispersion and list of publications (\*).

Species (habit)	Origen	Habitat	Disp	Reference
<b>Vial transport</b>				
<i>Eragrostis minor</i> (H)	S-Europe	Mosaic pavement	W	Küsel 1968, Kramer 1991
<i>Hordeum murinum</i> (H)	S-Europe	Roadside, tree disks	W	Hard & Kruckenmeyer 1990, Wittig 1995, Hard 1998
<i>Amaranthus albus</i> (H)	Central America	Railway areas	W	Passarge 1988, Brandes 1983a, b. 1993
<i>Corispermum leptopterum</i> (H)	E-Europe	Areas de transport, sand ruderal areas	W	Köck 1986, 1988, Passarge 1988, Langer 1995
<i>Salsola kali subs. Ruthenica</i> (H)	Eurasia	Railway areas	W	Gutte 1992, Brandes 1993
<i>Bunias orientalis</i> (H)	E- Europa	Roadside	W	Walter 1982, Heinrich 1985, Steinlein et al 1996
<i>Puscinellia distans</i> (H)	Coastal	Salt-loaded Roadside	W	Seybold 1973, Krach & Koepf 1980, Dettmar 1993
<i>Senecio inaequidens</i> (H)	E-Africa	Highway edges, ruderal areas	W	Werner et al 1991, Melzer 1991b, Kubbier 1996
<i>Buddleja davidii</i> (S)	E-Asia	Railroad, brownfields	W	Kreh 1952, Koster 1991, Schmitz 1991, Dettmar 1992
<b>Open Places</b>				
<i>Sisymbrium loeselii</i> (H)	N-America	Free ruderal sites	W	Gutte 1992
<i>Conizac canadensis</i> (H)	N-America	Free ruderal sites	W	Gutte 1992
<i>Chenopodium botrys</i> (H)	O-Asia S-Europe	Open debris of sand, gravel and coal sites,	W	Bornkamm & Sukopp 1971, Sukopp 1971, Dettmar und Sukopp 1991
<i>Ditrichia graveolens</i> (H)	S- Europa	Tailings	W	Gödde 1984, Dettmar 1992,
<i>Solidago canadensis</i> (H)	N- America	Old ruderal sites	W	Rebele 1986, Cornelius 1990 a, b, Adolphi 1995
<i>Robinia pseudoacacia</i> (T)	N-America	Old ruderal sites	Z	Kohler & Sukopp 1964 a, b, Kowarik 1990b, 1992b, 1996 c,d
<i>Ailanthus altissima</i> *** (T)	E-Asia	Ruderal, Buildings and green places	W	Kowarik & Böcker 1984, Gütte et al 1987, Kramer 1995
<b>Green Areas</b>				
<i>Galinsoga ciliata</i> (H)	S- America	Garden Beet	W	Schulz 1984, Krausch 1991
<i>Claytonia perfoliata</i> (H)	N- America	Sawmills	W	Fischer 1993b
<i>Impatiens parviflora</i> (H)	M-Asia	line up, park forest	W	Trepl 1984
<i>Veronica filiformis</i> (H)	Caucasus	Regularly mowed	W	Müller & Sukopp 1993
<i>Bidens frondosa</i> (H)	N- America	Water Margins	W	Köck 1988, Keil 1999
<i>Mahonia aquifolium</i> (T)	N- America	Hedges, park forest, ruderal site and urban forest	Z	Kowarik 1992b, Ringenberg 1994, Adolphi 1995
<b>Stonewall</b>				
<i>Cymbalaria muralis</i> (H)	S-Europe	Stonewall and Buildings	W	Brandes 1992, Adolphi 1995
<i>Pseudofumaria lutea</i> (H)	S-Europa	Stonewall	W	Segal 1972, Adolphi 1995
<b>Waste site</b>				
<i>Solanum lycopersicon</i> (H)	America	Sludge, waste sites	Z	Kunick & Sukopp 1975, Hetzel & Ullmann 1995

Although I only studied *A. altissima* population dynamics using matrix models, I think that the results are a good indicator of the aggressiveness of other species listed above, at least from the point of view of the control of such plants. Our reasoning is the following: if any of those species is already confirmed to be invasive, it is because it has a very high population growth rate. Thus, for control purposes, it may be not necessary to run demographics studies of other invasive species in Europe, but we can use our data on *A. altissima* as a criterion for deciding effective, realistic management control plans agreed by consensus of all stakeholders, either public or private sector.

Finally, climate change may produce more favourable conditions for invasive alien species. For example, in absence of control measures in Europe areas where global change increases local temperatures can have a tendency to proliferation of invasive plants from warm countries like *A. altissima*. Thus, the potential consequences of global change on the populations of *A. altissima*, joint to the impact of such species in the economy, is another reason to control this and other invasive species.

## **7.2 GENERAL CONCLUSIONS AND HOW TO CONTROL *Ailanthus altissima*.**

1. *Ailanthus altissima* predominate in urban environments along a urban-rural gradient .The species becomes less abundant an even almost impossible to find in forest areas.



2. The presence and abundance of *A. altissima* coincide with urban centers in the southern region of Hesse.
3. The abundance of *A. altissima* is related to human population density between and within cities and to larger train stations in spite of current control measures there.
4. *Ailanthus altissima* grows in all substrate types, although the best dry weight yields was obtained when it grown on bare soil. If there is a shortage of resources in the substrate *A. altissima* invests in the production of roots to get scarce resources and reduces to grow and develop. Previously established grasses can drastically suppress the germination and reduce the growth of *A. altissima*.
5. The population growth rate of *A. altissima* can increase 10 times each year and is determined by: the number of seeds produced, high germination rate and high survival of adult individuals. It contributes to enhance the high costs this species produces to public and private sectors.

In order to control *A. altissima*, we recommend the following:

1. To teach people –especially the owners of home gardens how not to confuse *Ailanthus altissima* (Götterbaum) with *Rhus hirta* (Essigbaum), which is a similar species very popular in gardens.

2. Pruning adult individuals just before flowering i.e. in April to June, to avoid excessive seed production.
3. Involving both public and private sectors in joint, coordinated actions to avoid the transfer of seeds or new *A. altissima* individuals from properties of each other; involve also private home gardens which are potential sources of seeds for train stations or other infrastructures.
4. Plant grass on places with bare soil in train stations and other infrastructures interested to be protected. Finally,
5. The role of trains and other vehicles on the spread of *Ailanthus altissima* remains poorly known because running such studies is prohibited; by eliminating such a prohibition and regulating scientific research on the subject, more information will be achieved on the process facilitating further decisions on how to control the expansion of *A. altissima*.

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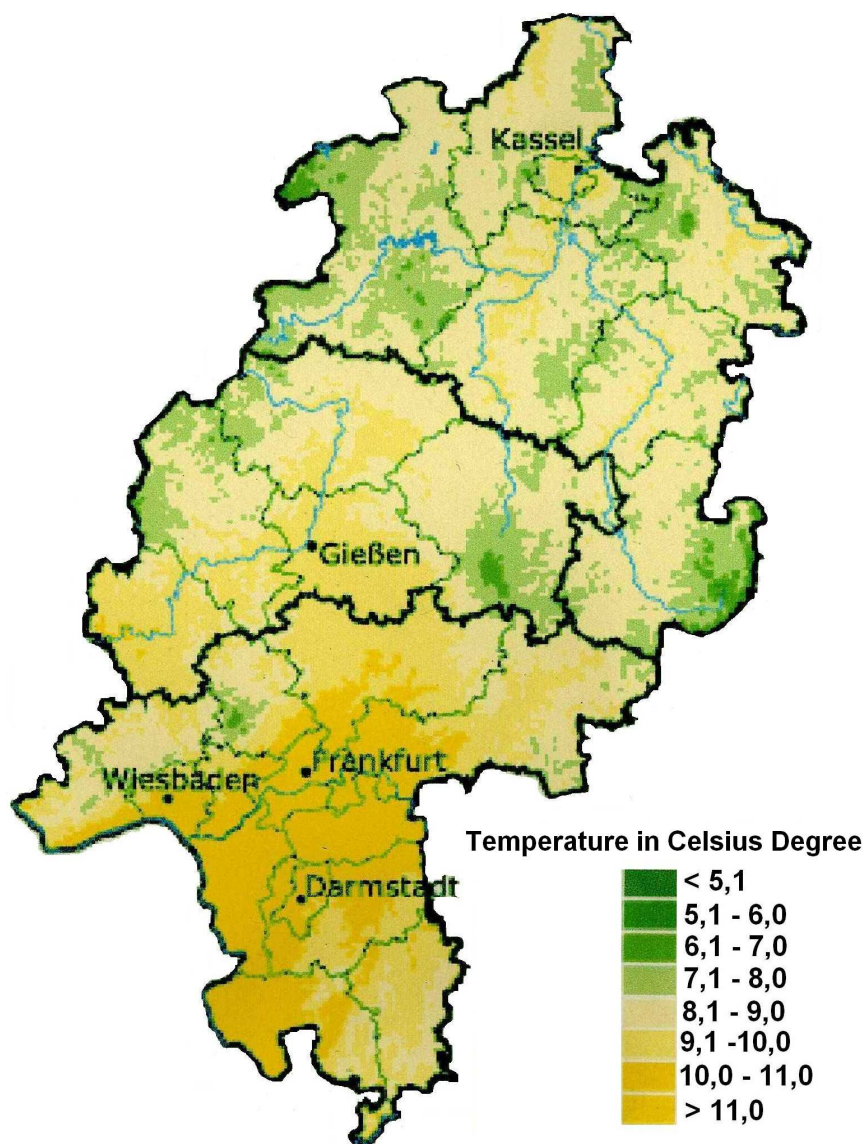
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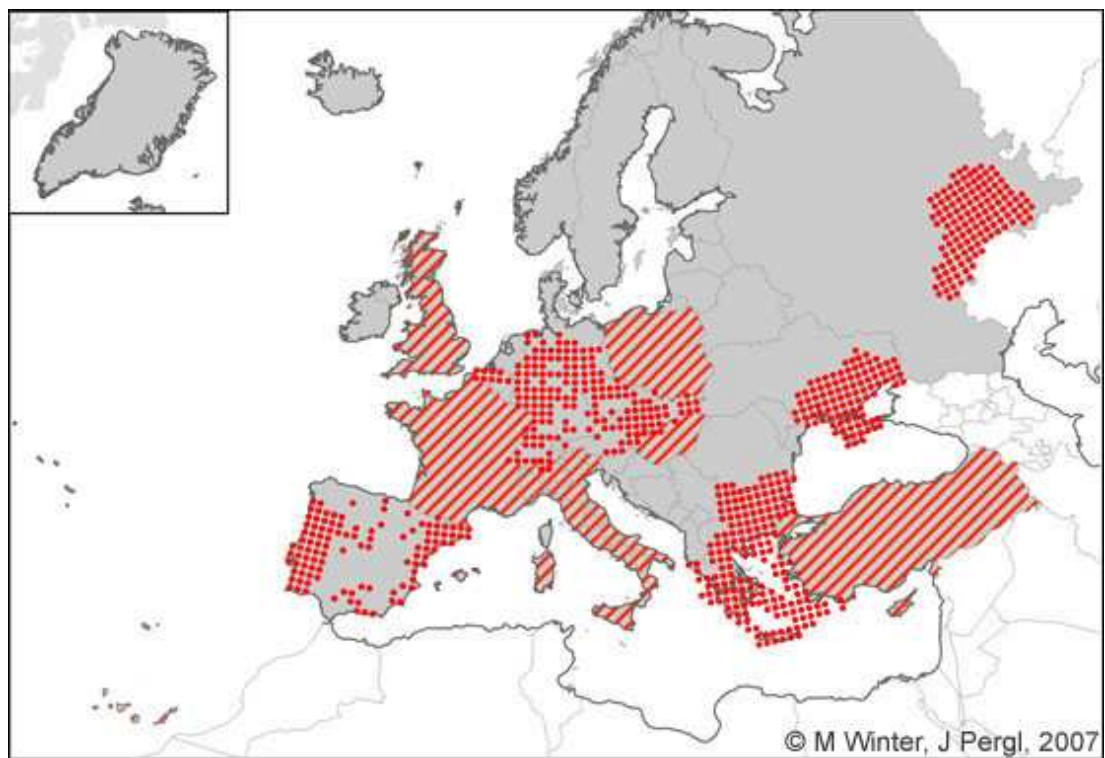
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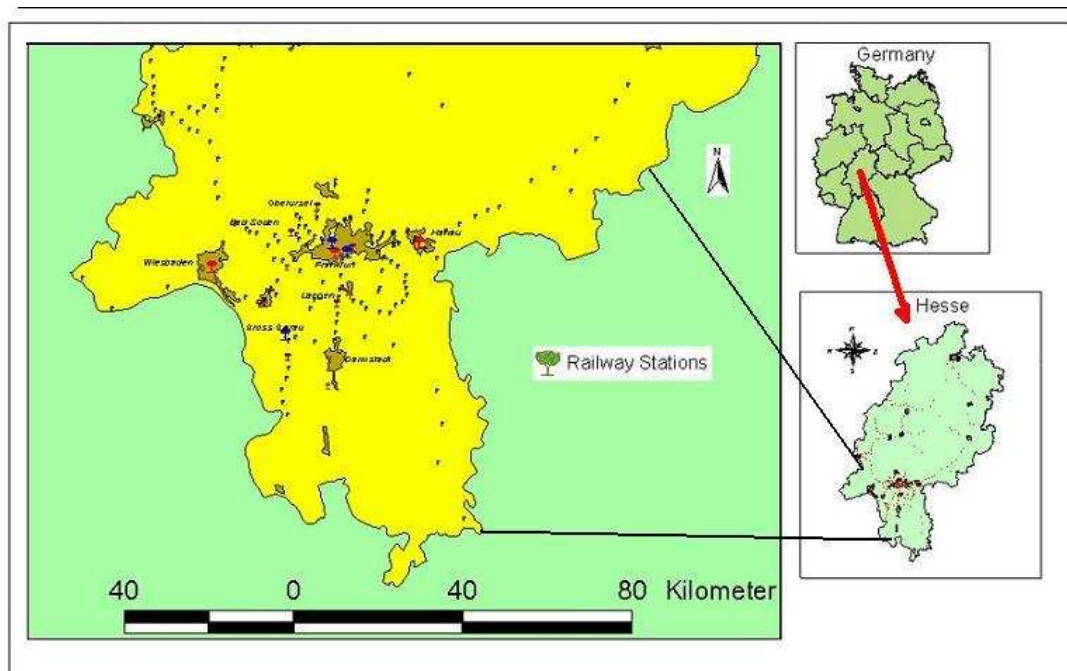
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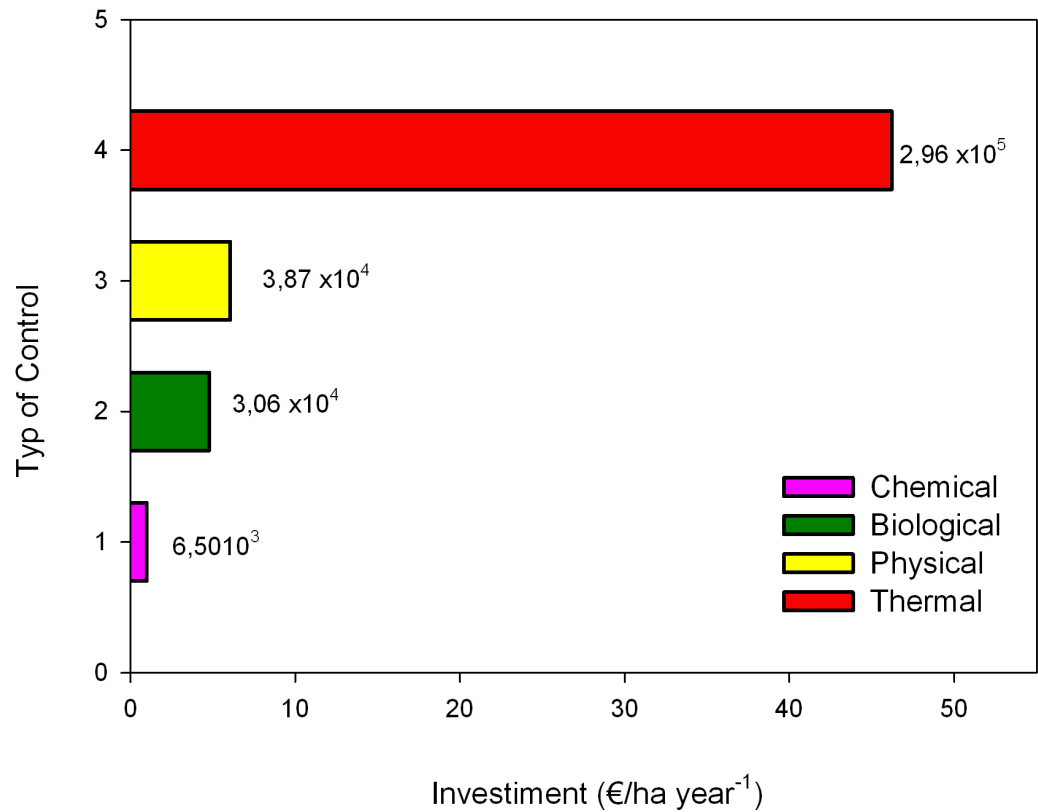
Means of Temperature in the last ten year (1991-2000) in the Federal State Hesse, Germany. Warmest areas coincide with dispersion of *Ailanthus altissima*.



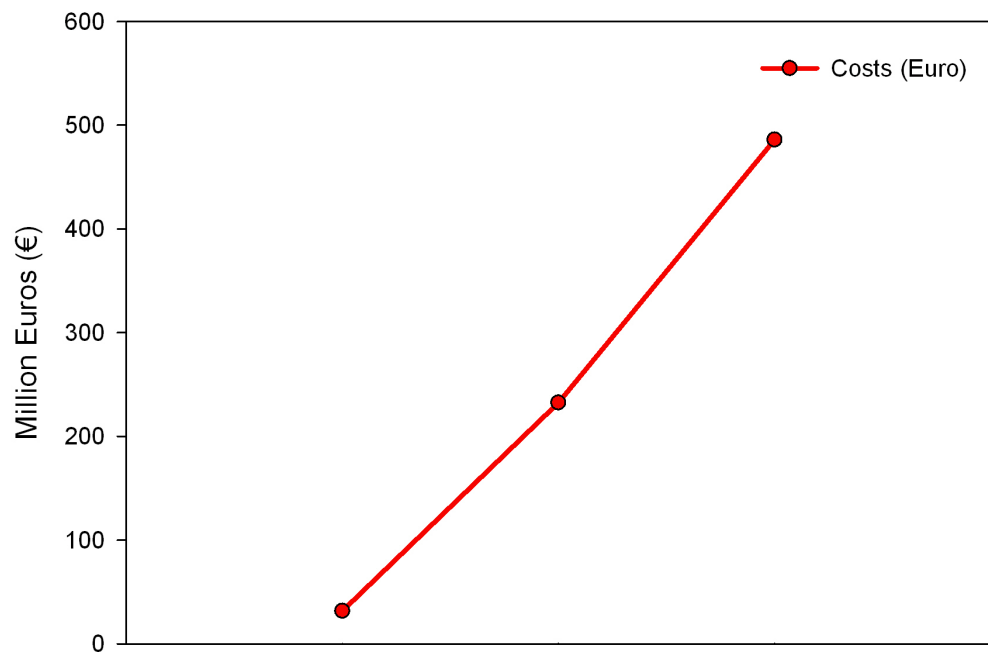
European distribution of *Ailanthus altissima*



Distribution of *Ailanthus altissima* in the Big Cities in Federal State Hesse, Germany



Money investment in the control of *Ailanthus altissima* in Federal State Hesse, Germany.



Economic costs caused by the treatment of allergy as a result of the invasion of species

Cost ocasioned by allergies treatment caused for the invasive apecies in Germany.

## CURRICULUMA VITAE

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EDUCATION		
DATE	TITLE	PLACE
2005now	PhD Student	George August University Göttingen Germany
2004	Master in Topical Biodiversity Management	San Paulo CEU and Sevilla University Spain
2001	Master in Forest Management and Biodiversity Conservation	Tropical Agricultural Research and Higher Education Center (CATIE) Costa Rica
1998	Degree in Biology (Botanic)	Autonomic University of Chiriquí
1998	Teacher Training (Biology)	Autonomic University of Chiriquí
1990	Bachelor of Science	Félix Olivares Contreras High School David

PROFESIONAL EXPERIENCE		
DATE	POSITION	PLACE
2005-now	Research Assistant	Johann Wolfgang Goethe and George August University, Germany
2002-2003	Research Professor	(ICADES) Autonomic University of Chiriquí
2002	Postgraduate Professor (Biodiversity)	Autonomic University of Chiriquí
2000-2001	Research Assistant	Tropical Agricultural Research and Higher Education Center (CATIE) Costa Rica
1997-1999	Clerk Computer Department	Autonomic University of Chiriquí
1995-1997	Student assistant Biology Labour	Autonomic University of Chiriquí

RESEARCH		
DATE	TITLE	PLACE
2005	Ecological characteristics and Economic Impact of non native <i>Ailanthus altissima</i> (Mill.) Swingle in Hesse, Germany	Germany
2003	She carried out projects for evaluation of plant and animal diversity in secondary forests in the area of Barrigon Gualaca after the construction of a hydroelectric. Project Esti-AES Panama	Panama
2003	Project children to school. Sociological research joint UNICEF and ICADMUF Panama	UNICEF Panama
2001	Since 2001 she has conducted research in forest fragmentation field, analyzing secondary forest structure, composition and their regenerative processes.	Panama and Costa Rica