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TREE-OF-HEAVEN (AILANTHUS ALTISSIMA): ENORMOUS AND WIDE POTENTIAL NEGLECTED BY THE WESTERN CIVILISATION

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ABSTRACT: The paper focuses on the main wood and timber characteristics and technological properties of the Tree-of-Heaven (*Ailanthus altissima (Mill.) Swingle*), derived during a two-year research project. Beside that, essential background information concerning the contradicting appearance and timber quality as well as the different point of view and cultural status of Ailanthus in China, as the country of origin, and in the "new" homelands North America and Europe are briefly discussed. The paper closes with recommendations concerning the usability of the timber and points out the wide field of application for furniture and construction purposes reflecting the enormous and wide potential which is as far as possible neglected by the Western civilisation.

KEYWORDS: Tree-of-Heaven, Ailanthus altissima, technological potential, physical and mechanical characteristics

1 GENERAL DESCRIPTION OF AILANTHUS ALTISSIMA

The Tree-of-Heaven (*Ailanthus altissima (Mill.) Swingle*), also known as ch'ou ch'un, stinking spring tree, false varnish tree or ghetto palm (e.g. [1,2,3,4,5]), is probably one or even the widest distributed "export product" of China. The species was first brought to Europe and North America by the monk Pierre d'Incarville (1740) [2] and by William Hamilton (1784) [3] in the meaning to colonise the "Chinese varnish tree". Due to its ornamental foliage, rapid growth and foreign and charming appearance the species became, despite the confusion, immediately favoured and wide applied in exclusive gardens and parks in estates and capitals (e.g. [2]). About 100 years later a second run on Ailanthus was initiated by the trial to get independent from China's silk-production through the establishment of sericultures in the 18th and 19th Century in the Central and South Europe as well as in England enabled by the implementation of the Ailanthus silkworm (*Philosamia cynthia*) in 1862 in Turin, Italy [3]. Nevertheless, the Ailanthus silkworm has been produced a robust, resistant and tough "Shantung silk" of high strength [1] but with lower coincidence and smoothness as than that from the mulberry silkworm (*Bombyx mori*) (e.g. [2,6,7]). Later, Ailanthus found wide application for reforestation on industrial regions, mining dumps and contaminated zones and as shelter belt due to its wide physiological amplitude characterised by a high resistance against pollution and unpretentiousness concerning growing conditions in regard to soil type, soil humidity, nutritional value as well as climate conditions (annual precipitation, mean annual temperature as well as longer periods of aridity) (e.g. [8,9,10,11,12]).

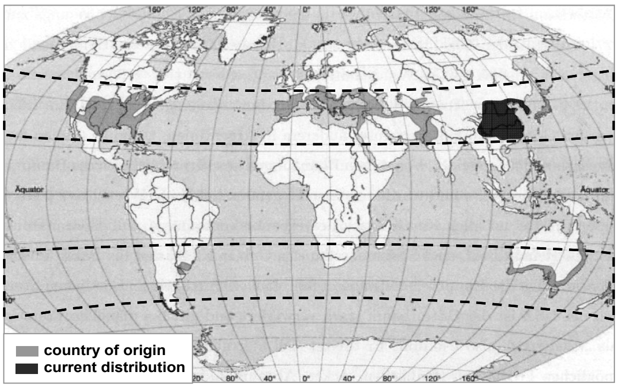

Figure 1: *Distribution (adapted from [11])*

The distribution of Ailanthus in the new "homelands", according to [11] is roughly defined between the 22nd and the 43rd latitude (Figure 1). In North America the distribution was probably additionally supported by the Chinese immigrant during the railway constructions [3] as well as in general by its distinctive pioneer nature in self establishment and distribution along highways (e.g.

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[2]) and waste lands. Beside that, Ailanthus is commonly characterised as shade-intolerant [13,14], urbanophile [15,16] and thermophile [11,17,18,19,20,21] tree species. In the Western civilisation the Tree-of Heaven is nowadays treated as undesirable weed, listed on the top of the forty most invasive woody angiosperm species [22] or just seen as bane. The aggressive (e.g. [23]) invasive and pioneer characteristic of Ailanthus (e.g. [3,24,25,26]) are diverse and include tremendous and early fruitfulness, enormous diasporas production ([27,28]), the tendency to develop stem- and root-suckers (e.g. [29,8,2,11,30]), the ability to clonical and rapid growth (1 ÷ 2 m / a if first grown, in case of coppice 3 ÷ 4 m/a in height, and 1 ÷ 2 cm / a in diameter), its samaras optimised for wind circulation, as well as the tendency to adapt the settled habitat according to its requirements (e.g. [31,25,26]).

Nevertheless, the Tree-of Heaven contributes to the culture of China, its country of origin, and is mentioned since the early beginning of lettering. The species' name consists originally of two ideograms, namely "mu" for timber and "ch'un" for spring, characterising the end of freezes when foliation starts [2]. As, beside the "Chinese varnish tree" (*Rhus verniciflua*), secondary most important timber species in China the Tree-of-Heaven experiences a strong forest management encouragement and utilisation which enables straight stems up to 15 m producing a widely applicable and high quality timber [2]. More than that, the tissues, especially the bark ("chu'un-po-p'i", "white bark of ch'un"), are constituents in the traditional Chinese medicine [2]. While some western publications mention poisonous effects and allergic reactions by humans in contact to Ailanthus due to allelopathic ingredients in its tissues the wood is for example used for steamers and the foliage as fodder for goats also nowadays or even for humans in scarce past times [2,3,32,33].

In contrast, in Europe and the United States the Tree-of-Heaven is nowadays often brought up under sparse conditions and careless and seen as worthless shrub (e.g. [2]). That's beside the fact that the species experienced an enormous boom listed as standard species of tree nurseries in the 19th Century in the east of the United States [2,28] as well as until the mid of the 20th Century e.g. in the eastern part of Austria [34]. Hu [2] already mentioned that the habitus of Ailanthus "… largely depends upon the man around it", discussing the contradicting appearance in China and the Western world. Nevertheless, the tree naturally of a diameter up to 1 m and a height up to 20 ÷ 25 m has in general a straight and widely knot free stem with characteristic lengthwise white cracked bark (e.g. [9]) and a medium extended crown of 8 ÷ 12 (15) m in diameter [34,9,35,36]. The foliage of Ailanthus is reminiscent of that of ash (*Fraxinus excelsior*) but larger in size. The resistance of the foliage or tissues of the Tree-of-Heaven against insects and fungi in general is, as many other properties, diverse discussed in the literature (see e.g. [37,3,4,38]). The harvesting is advised already in the age of 30 to 35 years (e.g. [4]).

Beside all above mentioned characteristics much information and publications of Ailanthus are available focusing on its invasive characteristics and postulating methods to control the enormous proliferation which leads at the end to unsatisfactorily but economically disastrous solutions. Nevertheless, publications concerning the timber properties, like density, strength and stiffness, and the usability in relation to profitability and motivation for encouragement of this species are missing. Some comprehensive examinations related to the characteristics of small knot free specimens ("clear wood") are published in [39,40,41,42].

Encouraged by an Austrian forest owner who experienced an enormous invasive infiltration of Ailanthus nearly over the half of a 1,200 ha forest area within only two decades a two-year project was established with the main target of research concerning the utilisation potential of the timber instead of unsuccessfully and economically disastrous combating. The practical experiences in processing followed by an intensive testing program on defect free wood specimens ("clear wood") and on boards of construction size ("construction timber") in tension and compression parallel to grain as well as in bending enabled the examination of utilisation potentials of this outstanding wood species. In addition degrees of swelling and shrinkage in various climate conditions, characteristics concerning processing and many more properties were investigated and are given afterwards (for details see [43]).

2 MATERIAL AND METHODS

The used material, harvested at Esterhàzy Betriebe GmbH / Eisenstadt, originates from the north-eastern part of Austrian's Pannonian region. The trees with a mean diameter in breast height of 20 cm were harvested in autumn 2007 on three different places HR1 to HR3 and cut into 3 m logs. The growth regions with altitudes between 150 m and 280 m are characterised by a sandy loam, coppice management and a high yield power (for details see [44]). Whereas the forest stocktaking data showed no remarkable differences between the harvesting regions the median age of the trees in HR1 was in comparison to HR2 and HR3 45 a to 27 a and 22 a respectively, leading to nearly the half of the annual diameter increment in HR1.

The cutting process into posts of 25 mm to 45 mm thickness and 8 mm thick lamellas immediately after harvesting as well as further processing steps like kiln drying to 12 % moisture content, planning and trimming were accomplished at the Rutan Holzindustrie GmbH / Fürstenfeld / Austria. The lamellas were used for the production of a three-layered light-building board with a core of cross-grained balsa wood (thickness = 20 mm = 4 + 12 + 4), as well as for cross-laminated boards of five layers (thickness = 22 mm = 5 · 4.4). Furthermore, lamellas were additionally used for steaming and roasting tests. The specimens for the static test as well as for the determination of degrees for shrinkage and swelling were cut out from the posts. The test plans for the "clear wood" and the "construction timber" specimens are given in Table 1 and Table 2.

Table 1: *Test plan for "clear wood"*

Applied tests [--]	Lot sizes [#]	Dimensions l / w / d [mm/mm/mm]
Four-point-bending acc. to DIN 52186 [45]	160 #	400 / 20 / 20
Tension II acc. to DIN 52188 [46]	160 #	470 / 20 / 15
Compression II acc. to DIN 52185 [47]	160 #	60 / 30 / 30
Shear acc. to EN 392 [48] Polyurethane (PUR) Melamine-Urea-F. (MUF) Resorcin (RES) Poly-Vinyl-Acetat (PVAC) Shear tests on wood	300 # 60 # 60 # 60 # 60 # 60 #	30 / 40 / 40
Hardness (Brinell) acc. to EN 1534 [49] light-building board (LBP) cross-layered board (5SP)	65 # 35 # 30 #	300 / 200 / 20
Swelling / Shrinking acc. to DIN 52184 [50]	30 #	100 / 20 / 20

Table 2: *Test plan for "construction timber"*

Applied tests (acc. to EN 408 [51]) [--]	Lot sizes [#]	Dimensions l / w / d [mm/mm/mm]
Four-point-bending flatwise (fw): MOE edgewise (ew): MOE + MOR	30 # 30 # 30 #	2,660 / 140 / 35
Tension II	30 #	2,200 / 140 / 35
Compression II long fixing distance (l) short fixing distance (s)	30 # 5 # 25 #	-- 210 / 140 / 35 120 / 140 / 35

All destructive and non-destructive tests were carried out acc. to EN or DIN standards. From all specimens the dimensions and the mass for calculating the density as well as the moisture content and the failure characteristics were logged. Furthermore, the parameters like the angle between the horizon and the tangent on the annual growth ring (α), the mean annual ring width (ARW) as well as the radial position within the log (RP) were determined on all "clear wood" specimens. The "construction timber" was in addition tested by means of Sylvatest / Concept Bois Technology and Timber Grader MTG / Brookhuis Micro Electronics BV to determine the dynamic E-modulus on the basis of ultrasonic speed and eigenfrequency, respectively. To get a first idea of grading relevant characteristics and its influence on the mechanical properties knots and other growth characteristics were logged and the data used for statistical analysis.

3 EXPERIENCES AND TEST RESULTS

The further subchapters are split into the topics appearance, experiences concerning the machinability and processability of the timber and a section comprising the results of the static tests on "clear wood" and "construction timber".

3.1 THE APPEARANCE

The rind-porous, hard and light-yellow coloured wood of *Ailanthus altissima* with facultative orange to black stripes [39,52,42] has a very attractive and expressive texture more or less comparable to ash (*Fraxinus excelsior*). The sapwood normally contains of 4 ÷ 10 annual growth rings [41,44]. The compulsive heartwood [42] is only marginally darker in colour than the sapwood. Due to its distinctive rays the appearance, especially the tangential surface, is sometimes seen as attractive as that of the sycamore tree (*Acer pseudoplatanus*).

3.2 CHARACTERISTICS CONCERNING THE MACHINING, THE PROCESSING AND THE USABILITY

According to the experiences made within this project and in agreement with e.g. [53,39,41,12] the wood and timber of Ailanthus is well machinable and processable, especially sawing, moulding, planning, drying and gluing, are in general more or less akin to ash. This enables the consideration and utilisation of experiences as well as the application of the same process parameters made with and known for ash wood and consequently the efficient integration of *Ailanthus altissima* in existing production processes. Also the properties concerning sanding, polishing, and surface treatment processes in general are seen as satisfactorily for commercial as well as for industrial applications (e.g. [1,39,41,12,42]). The durability, as relevant property for exposed outdoor applications, is diverse discussed in the literature and ranges from "durable" (especially the outer regions of the heartwood [54,53,2,7]) to "not durable" [34,41].

3.3 PHYSICAL / MECHANICAL PROPERTIES

The further subchapters comprise the physical and mechanical characteristics of *Ailanthus altissima* which were investigated within this research project. The test results are given by the main statistics containing the range (min / max), the expectable or central values (mean and median) as well as the coefficient of variation (CoV) as a measure of dispersion. Conform to the general assumptions for the representation of wood and timber properties by statistical distribution models the normal distribution (ND) and the lognormal distribution (LND) can be seen as suitable to characterise the density (ND) and the moduli of elasticity (LND) as well as the strength values (LND), respectively.
A comprehensive illustration of all results and background information is given in [55].

3.3.1 Clear wood

The following tables contain the statistics gained from tests on "clear wood". The mean density of the herein investigated *Ailanthus altissima* specimens was around 650 kg/m³. The determined densities are in line with [56,40] but higher than in [57,41]. The specimens of the tensile tests showed a remarkable higher mean density of $\rho_{12,t,mean} \approx 680$ kg/m³. The statistical analysis concerning the dependencies between the strength and stiffness properties and the additional determined parameters α, ARW, RP showed poor and insignificant results. The influence on the grain angle α on the test results of the tensile and bending strength only reflected an expected slight decrease of the dispersion in case of nearly vertical annual growth rings (45° ≤ α ≤ 90°). To clarify and compress the test results the statistics are calculated under consideration of all results relevant for each characteristic.

Table 3: *Statistics of compression test results on "clear wood" parallel to grain*

Compression	ρ_{12} [kg/m³]	$E_{c,0,g,12,app}$ [N/mm²]	$f_{c,0,12}$ [N/mm²]
N #	160 #	159 #	159 #
Min	554	5,880	35.6
Mean	**645**	**9,080**	**48.5**
Median	642	8,990	48.7
Max	740	12,770	57.9
CoV [%]	**7.1%**	**16.8%**	**10.9%**

The statistics of the compression tests parallel to grain are given in Table 3. The mean compression strength with $f_{c,0,12,mean,CW} \approx 50$ N/mm² confirms the expectations of comparable properties to ash and more or less the results of [56,40,41,58]. The E-modulus in compression was computed based on the global measured strain but without deformations of the testing device. Nevertheless, due to probably not perfect parallelism of the end grain surfaces an uneven applied load and consequently deviations from the cross section area used in computing the E-moduli could not be excluded. Due to that the values are given as apparent E-moduli and do not confirm the expectable stiffness as easily visible by comparing $E_{c,0,mean,CW}$ with $E_{t,0,mean,CW}$ and $E_{m,mean,CW}$. Due to unavoidable deficiencies in global deformation measurements the tests in tension and bending were accomplished by means of additional local deformation measurement devices.

Table 4: *Statistics of tensile test results on "clear wood" parallel to grain*

Tension	ρ_{12} [kg/m³]	$E_{t,0,l,12}$ [N/mm²]	$f_{t,0}$ [N/mm²]
N #	158 #	145 #	85 #
Min	591	7,430	104.0
Mean	**678**	**13,450**	**151.4**
Median	671	13,630	--
Max	797	18,040	--
CoV [%]	**7.7%**	**16.6%**	**16.4%**

The tensile tests were performed by means of a 20 kN load cell which – contrary to the expectations – only enabled testing to failure in half of all cases. Knowing that all "not failed" specimens are able to carry more than 20 kN load the expectable tensile strength and some more statistics were calculated by means of censored data analysis (see Table 4). The mean value with $f_{t,0,mean,CW} = 150$ N/mm² is 36 N/mm² higher than published by [40] but more than realistic considering the lowest value in herein accomplished tests with $f_{t,0,min,CW} = 104$ N/mm².

Table 5: *Statistics of four-point-bending-test results on "clear wood" parallel to grain*

Four-point-bending	ρ_{12} [kg/m³]	$E_{m,l,12}$ [N/mm²]	f_m [N/mm²]
N #	120 #	132 #	103 #
Min	556	7,610	78.7
Mean	**656**	**14,590**	**105.6**
Median	653	14,080	105.1
Max	755	22,790	135.2
CoV [%]	**5.7%**	**22.5%**	**10.4%**

The statistics of the four-point-bending tests are shown in Table 5. As expected, the bending strength is in between the compression and tensile strength with a mean value of $f_{m,mean,CW} = 105$ N/mm² which corresponds with the upper boundary of the data supported in the literature within the range of 81 N/mm² ÷ 104 N/mm² [40,39,41,42]. The mean bending-E-modulus as well as the $CoV(E_{m,CW})$ appear unexpected high in comparison to the tensile test statistics. The mean values given by [39,41,42] are between 9,400 N/mm² and 12,300 N/mm². It is assumed that the E-moduli given in the literature are computed based on the global deflection including shear strain and deformations caused by local indentations, and not based on local measurements of solely bending deflections as done in the herein referred tests.
The statistics of the hardness (Table 6) bases on measurements accomplished on two board materials (LBP and 5SP) and therefore not direct transferable to the hardness potential of "clear wood" specimens but relevant e.g. for furniture, parquet and threads. The mean hardness of LBP is lower than that of 5SP. The difference is not as high as expected considering the balsa core in LBP. Nevertheless, the mean hardness capacity of $f_{c,90,HB,mean} \approx 25$ N/mm² is much lower than $f_{c,90,HB,mean} \approx 30$ N/mmm² given by [56,42].

Table 6: *Statistics of hardness-test results acc. Brinell on light-building-boards (LBP) as well as on cross-layered boards (5SP)*

Hardness (Brinell)	$f_{c,90,HB,5SP}$ [N/mm²]	$f_{c,90,HB,LBP}$ [N/mm²]
N #	29 #	35 #
Min	17.7	20.6
Mean	**25.7**	**24.1**
Median	26.5	23.9
Max	34.5	28.6
CoV [%]	**16.8%**	**7.8%**

The statistics of the shear strength of the wood and of the four tested adhesive types are given in Table 7. The applied shear test configuration acc. to EN 392 [48] is in general considered for the glulam production quality control but herein used for estimating the shear performance of the wood and for the identification of reasonable adhesives types for *Ailanthus altissima*. The mean shear strength of $f_{v,090,mean}$ = 11.5 N/mm² is lower than given in [39] who postulated a value of $f_{v,090,mean,CW}$ = 15.4 N/mm² ($\rho_{12,mean}$ = 530 kg/m³). Furthermore, in testing RES or PVAC it was not possible to provoke a predominant shear failure in the glue line. Comparing the $CoV(f_{v,090})$ of all test results of all four adhesives, which is of relevance for a robust production processes, the results of RES and PUR had the lowest *CoV*'s reflecting best performance. Nevertheless, PUR-specimens showed the lowest shear strength capacity. As a consequence the RES is in a first view seen as the best choice.

Table 7: *Statistics of shear test results on glue lines as well as on wood itself: "clear wood" specimen*

Shear	$f_{v,090}$ [N/mm²]				
	100%	≤ 25% wood failure			
	wood	PUR	MUF	RES	PVAC
N #	63 #	23 #	8 #	0 #	0 #
Mean	**11.5**	**10.4**	**12.2**	**--**	**--**
Median	11.8	10.0	13.0	--	--
CoV [%]	13.8%	7.0%	9.9%	--	--
$\rho_{12,median,fail}$ [kg/m³]	637	655	555	--	--
$\rho_{12,median,all}$ [kg/m³]	637	655	627	629	--

3.3.2 Construction timber

The herein tested ungraded "construction timber" suffered from distinctive growth characteristics like local and global grain deviations, especially single knots, knot clusters and pre-broken tree tops. This is due to the fact that the harvested Ailanthus originates from forests where this species has been partly heavily combated by the forest management. Due to that the strength and stiffness values cannot be taken as representative for the expectable timber capacities achievable in managed Ailanthus timber forests. Nevertheless, the results are important in relation to the recorded characteristics and together with the knowledge of the capacity of "clear wood" as upper boundary for the characteristics achievable in the highest strength grading classes.

Table 8: *Statistics of compression test results on "construction timber" parallel to grain*

Compression	ρ_{12} [kg/m³]	$E_{c,0,l,12}$ [N/mm²]	$f_{c,0,12}$ [N/mm²]
N #	25 #	25 #	24 #
Min	581	9,820	35.3
Mean	**638**	**12,720**	**41.6**
Median	624	12,100	40.9
Max	732	17,010	50.8
CoV [%]	**5.9%**	**15.6%**	**9.4%**

The statistics are summarised in Table 8 to Table 10. The mean densities of the tensile, compression and bending tests with $\rho_{12,mean,CT} \approx 640$ kg/m³ are nearly equal enabling well comparable data sets. The mean E-moduli are highest in compression and lowest in tension parallel to grain corresponding to the interaction of tension and compression in case of bending stresses and due to the fact that a knot in compression may stiffen a specimen whereas tension sections with knots exhibit a lower stiffness than the surrounding "clear wood". The lower value of $E_{m,l,12,ew,mean}$ and the higher $CoV(E_{m,l,12,ew})$ compared to $E_{m,l,12,fw,mean}$ and $CoV(E_{m,l,12,fw})$ in Table 10 reflect the higher influence of local growth characteristics (e.g. knots) situated near the small faces if the boards are tested edgewise and not being tested flatwise.

Table 9: *Statistics of tensile test results on "construction timber" parallel to grain*

Tension	ρ_{12} [kg/m³]	$E_{t,0,l,12}$ [N/mm²]	$f_{t,0}$ [N/mm²]
N #	31 #	31 #	30 #
Min	564	9,150	13.5
Mean	**643**	**12,320**	**42.1**
Median	640	12,190	40.7
Max	742	17,240	85.0
CoV [%]	**6.5%**	**17.1%**	**46.9%**

Table 10: *Statistics of four-point-bending-test results on "construction timber" parallel to grain*

Four-point-bending	ρ_{12} [kg/m³]	$E_{m,l,12,fw}$ [N/mm²]	$E_{m,l,12,ew}$ [N/mm²]	$f_{m,ew}$ [N/mm²]
N #	31 #	30 #	31 #	31 #
Min	583	9,040	6,680	13.6
Mean	**646**	**12,620**	**12,420**	**51.3**
Median	641	12,620	12,380	55.4
Max	710	16,240	16,900	95.6
CoV [%]	**5.5%**	**13.5%**	**20.6%**	**43.1%**

4 CONCLUSIONS

The paper summarises the outcomes of a comprehensive two year research project for investigating the tree and timber species *Ailanthus altissima* and to create fields of applications for a species which is well established in the country of origin but lacks of acceptance in the already since 300 years effective and in the mean-time by self-distribution colonized "new" homelands all over the world.

Table 11: *Comparison between the main physical and mechanical characteristics of Tree-of-Heaven and ash: "clear wood", mean values*

Property	[--]	**Mean-values Ailanthus**	**Ash**	**Δ** [%]
$\rho_{12,mean}$	[kg/m³]	**650**	690	– 5.8 %
$\beta_{V,mean}$	[%]	**13.5 %**	13.2 %	+ 2.3 %
$f_{c,0,12,mean}$	[N/mm²]	**48**	52	– 7.7 %
$f_{m,12,mean}$	[N/mm²]	**105**	105	± 0.0 %
$f_{t,0,12,mean}$	[N/mm²]	**150**	165	– 9.1 %
$f_{v,090,12,mean}$	[N/mm²]	**12**	12	± 0.0 %
$f_{c,90,HB,12,mean}$	[N/mm²]	**26**	39	– 33.4 %
$E_{0,12,mean}$	[N/mm²]	**14,000**	13,400	+ 4.5 %

Therefore, Table 11 summarises the main characteristics of *Ailanthus altissima* determined on “clear wood” and compares them to ash [59] as the associated reference wood species. The results are in line with the experiences made by processing the green and dry wood and timber and confirm the possibility of a similar treatment and machinability of Ailanthus and ash. This enables the dynamic adoption of Ailanthus in consisting production processes. The appealing and distinctive texture of Ailanthus in combination with its attractive name simplifies advertising and inspires marketing processes for niche products nowadays but probably also for mass products in the near future. As a consequence, it is on us to decide how we came up with already established invasive species. We have to answer if we should keep on economic disastrous combating or if we are willing to integrate and utilise the species: INTEGRATION vs. AVERSION!

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