Introduction

German chamomile (Matricaria chamomilla L. (syn. M. recutita (L.) Rauschert)) is a valuable medicinal plant, delivering essential oil and dried flower heads. Traditionally German chamomile is used as herbal tea, primarily effective against gastric and intestinal complaints (Ravindran and Pillai 2012). To develop high quality cultivars with desired agronomical traits breeding efforts have been undertaken for more than 60 years (Franke 2009). Pank and Bluethner (2009) expressed the aims of breeding as an increase of medicinally valuable components and suitability for mechanical harvesting.

Specific crossings are the method of choice to combine desired maternal and paternal traits and/or to use heterosis effects in outcrossing crops (Wricke and Weber 1986). In hermaphroditic Asteraceae like chamomile, possible self-fertilization is to be avoided to ensure fertilization with the chosen crossing partners (Becker 1993, Richards 1997, Stoskopf et al. 1993). A—vegetatively propagated—mother line of self-incompatible (SI) plants could form an ideal base for crossings, ensuring the provided partner plants to be the father and the seeds deriving from mother plants to be progenies of desired parents. Without using SI, mother plants would have to be castrated manually or chemically, which would cause enormous stress and decrease reproducitivity (Becker 1993).

The challenge in this scope is to develop suitable strategies to maintain self-incompatibility (SI), either vegetatively by recurring cuttings or generatively by using a suitable maintainer line as partner. Other papers already stated the search for genetic constitution of maintenance of SI (e.g. Sijacic et al. 2004, Vieira and Charlesworth 2002). In consequence, the present research focused on exploring the effects of vegetative or various generative maintaining methods on SI occurrence in a population of chamomile plants. Furthermore, partners with differing SI constitutions were individually crossed to get an idea of maternal or paternal inheritance and to work towards best breeding results in the next generation. As already done for other intrinsic values of German chamomile (Franz 1993), investigating the heritability of the SI trait would give an answer to the question of suitability of individual selection procedures in breeding. Some previous work on self-incompatibility in German chamomile showed that there is a significant effect of cultivar on...
this trait and that diploid cultivars tend to stronger self-incompatibility (higher outcrossing rate) than tetraploid ones (Faehnrich et al. 2013a). Therefore focus was laid on diploid (2x) cultivars in this study. Four diploid accessions (‘Degumille’ (DEG), ‘Germania’ (GER), Promyk’ (PRO) and ‘USA’ (USA)) and two tetraploid ones (‘Hungarian 1’ (HUN 1), ‘Lutea’ (LUT)) were comprised in the experiments. Normally genetics of plants should not change during life time; solely a certain genetic variability and consecutively an occasional loss of chromosomes in auto-tetraploid genotypes (like in the colchicine induced 4x-accessions of chamomile) could happen (Cassells and Morrish 1987, Faehnrich et al. 2013b, Gottschalk 1976, Mar’yakhina and Butenko 1974, Otto 2007). According to earlier trials with German chamomile, exploring ploidy level and formation of aneuploidy at the beginning and at the end of a five month lasting period, no directed change or loss of chromosomes should be expected (Faehnrich 2013, personal communication). Genetic stability therefore could be assumed and phenotypic alteration should be due to environmental changes. Nevertheless, differing gene expression as a response to environmental changes/stress and/or elapsed time/senescence concerning labile phenotypic traits is an often observed effect in commercial plants (Havaux 2014, Li et al. 2012, Wen et al. 2015, Westneat et al. 2015). This effect could also play a role in recent maintenance experiments, and could be a reason for the high environmental influence on SI in spite of the high heritability values. However, cultivar specific reactions suggest possible certain SI maintaining strategies.

**Materials and Methods**

**General**

To start the recent trials a population of 220 German chamomile (Matricaria recutita (L.) Rauschert) plants among six varieties (‘Degumille’ (DEG), ‘Germania’ (GER), ‘Hungarian 1’ (HUN 1), ‘Lutea’ (LUT), ‘Promyk’ (PRO) and ‘USA’ (USA)) was grown in the green house of the University of Veterinary Medicines, Vienna (Table 1). ‘Degumille’, ‘Germania’, ‘Lutea’, and ‘Promyk’ are described varieties since 1977, 1962, 1995 and 1992, respectively (Heine et al. 2009). ‘Hungarian 1’ is an accession provided by the Faculty of Horticulture of the University of Budapest and was proven to be 81% tetraploid (Faehnrich et al. 2013a). ‘USA’ is a trade accession from the referring country. ‘Degumille’, ‘Germania’, ‘Promyk’ and ‘USA’ are diploid; ‘Lutea’ is a tetraploid variety (Plescher and Sonnenschein 2013, Schilcher 1987).

**SI-examination**

Cuttings were produced from each plant of the starting population before evaluation of self-incompatibility. To prove SI, single plants were isolated with micro-perforated Crispac-bags (Baumann, Waldenburg, Germany) and hand pollinated not fewer than three times. As soon as flower heads ripened (ray flowers turned downwards, disk flowers from yellow to brown), three flower heads were collected, dried in an oven (30°C, not shorter than one week) and seed set was examined under light microscope at 100-fold magnification. Ripe and normal shaped achenes (with a length of 1–2 mm and a width of app. 0.3 mm, striped, slightly curved) were assumed to bear fertile seeds and were counted. Plants displaying a negative seed set in all three examined flower heads were determined as self-incompatible.

**Vegetative maintenance**

Plants raised from cuttings from initially selected SI-plants were kept as the first parental population (P1). In Oct. 2014 this P1 population included 61 individuals among five chamomile varieties (Table 1). The first part of the trial maintained the individuals (partly by generating cuttings) and therefore the genetic material of P1 for six months, until new SI determination in March 2015. Except of some perished plants, this population survived and was called P2. Thereby the SI maintenance over varying environments (elapsed time, changing growing conditions) at stable genetic conditions could be assessed (Table 1).

**Table 1.** Total number of plants in the starting population and number of evaluated plants in each other determined population of the trial (N). Mean values of SI-development (SI = 1.00, non SI = 0.00 per plant), standard deviation (SD) of all mean values in all determined populations, separated by variety. Missing values indicate that there are no evaluable plants available in the respective group.

| Variety | N  | Mean  | SD   | N  | Mean  | SD   | N  | Mean  | SD   | N  | Mean  | SD   | N  | Mean  | SD   |
|---------|----|-------|------|----|-------|------|----|-------|------|----|-------|------|----|-------|------|
|         | P1 |       |      | P2 |       |      | F<sub>1</sub> |       |      | F<sub>1</sub> |       |      | F<sub>1</sub> |       |      | F<sub>1</sub> |       |      |
| LUT     | 40 | 0.20  | 0.41 | 0  |       |      | 3   | 0.33  | 0.58 | 0  |       |      | 2   | 0.50  | 0.71 |
| HUN 1   | 49 | 0.36  | 0.50 | 14 | 1.00  | 0.00 | 6   | 0.50  | 0.55 | 0  |       |      | 0   | 0     | 0    |
| USA     | 41 | 0.00  | 0.00 | 0  |       |      | 0   | 0     | 0    | 0  |       |      | 0   | 0     | 0    |
| GER     | 40 | 0.38  | 0.52 | 1  | 1.00  | 0.00 | 2   | 0.00  | 0.00 | 0  |       |      | 1   | 0.00  | 0.33 |
| DEG     | 40 | 0.34  | 0.48 | 38 | 1.00  | 0.00 | 16  | 0.75  | 0.45 | 68 | 0.82  | 0.38 | 35  | 0.36  | 0.36 |
| PRO     | 10 | 0.60  | 0.55 | 1  | 1.00  | 0.00 | 2   | 0.50  | 0.71 | 0  |       |      | 0   | 0     | 0    |
| Total   | 220| 0.31  | 0.46 | 61 | 1.00<sup>a</sup> | 0.00 | 26  | 0.62<sup>c</sup> | 0.50 | 71 | 0.80<sup>d</sup> | 0.40 | 36  | 0.86<sup>e</sup> | 0.35 |

<sup>a</sup> Different letters indicate significant differences at probability error level α = 0.05 between P1 and P2.
<sup>c</sup> Different letters indicate significant differences at probability error level α = 0.05 between P1 and crossing versions of F<sub>1</sub>.
<sup>d</sup> Different letters indicate significant differences at probability error level α = 0.05 between P1 and F<sub>1</sub> total.
<sup>e</sup> Different letters indicate significant differences at probability error level α = 0.05 between P1 and F<sub>1</sub> crossing versions in ‘Degumille’ (DEG).
**Table 2.** P-values after two way univariat analyses of variance for the influence of generation/crossing/environment, cultivar and interactions, respectively, on the occurrence of self-incompatibility (SI) in the relevant populations (databases)

| Factor of influence                        | P1 + P2 | P1 + F1 crossing versions | P1 + F1 total | P2 + F1 total | F1 crossing versions |
|--------------------------------------------|---------|---------------------------|---------------|--------------|---------------------|
| Generation/crossing/environment           | <0.001* | 0.001*                    | 0.004*        | 0.143        | 0.257               |
| Cultivar                                   | 0.064   | 0.606                     | 0.282         | 0.014*       | 0.345               |
| Interactions                               | 0.057   | 0.207                     | 0.126         | 0.241        | 0.416               |

* Significant at a level of error probability of α = 0.05.

**Generative maintenance**

The second part of the trial used cuttings of the P1 population for intra-cultivar crossings. Defined SI plants of P1 as mother were crossed with defined SI plants as father (SI × SI) and with ‘normal’, not SI evaluated plants (so called NSI plants) as father (SI × NSI). The third version (NSI × SI) incorporated crossings of NSI plants as mother and SI plants as father. To avoid misleading fertilization all plants were isolated as a whole with Crispac-bags and hand pollinated. Self-fertilization of NSI mother plants therefore could happen and was not eliminated to avoid additional stress through emasculation. Total F1 generation comprised 215 progenies within all three crossing versions, among which 143 could be SI evaluated (Table 1).

**Statistics**

Statistical analyses were performed with SPSS 20 program (IBM, Armonk, USA). Experimental unit was the single plant individual. Influence of cultivar and environment, generation and/or crossing version on SI development in defined groups of plants was assessed by two way univariat analyses of variance. If applicable, post hoc tests were performed according to Student-Newman-Keuls. All statistical analyses were conducted at a level of probability of 5%. Determined SI (3 × 0 seeds) was given the value 1.00 (equal to 100% SI), plants with positively evaluated seed set were given the value 0.00 (equal to non SI). The mean values displayed in tables vary between 0.00 and 1.00, indicating SI percentages of the respective group between 0% and 100%. In case fewer than three flower heads ripened to seed harvesting stage, data of this plant were not included in the calculations. Cross tables and chi-square tests (Pearson) evaluated the concordance of SI distribution with expected values. Realized heritability (h²) of SI was calculated via equation $h^2 = R/S$ (Becker 1993). S indicates the difference of mean of the starting population and the mean of the SI selected population P1 and R indicates the success of selection, i.e. the difference between the mean of the starting population and the mean of the F1 after SI × SI.

**Results**

**Influence of environment—comparison of P1 and P2**

To evaluate the influence of changing environment at stable genetics, SI appearance of P1 in Oct. 2014 compared with P2 in Mar. 2015 was tested over all cultivars/varieties by analysis of variance. The environment showed highly significant influence with a p-value of <0.001. Cultivar turned out not being significant (p = 0.064). Still, this p-value indicates a certain tendency, even underlined by the p-value for the interaction cultivar*environment of 0.057 (Table 2). Despite of non-significant results, post hoc tests for the influence of cultivars on SI maintenance displayed two subgroups (Table 3). The high mean value of ‘Lutea’ (1.00) over both populations (P1 and P2) can be neglected, as ‘Lutea’ only occurs in P1 (Table 1). Nevertheless, remarkable is the high value of ‘Degumille’ of 0.93, as this can be seen as a sign of a high SI stability over changing environments for this cultivar (Table 3). Also the strong tendency of the cultivar*environment interaction as described above underlines this approach. Therefore, a special focus on heritability calculations of ‘Degumille’ will be given. Chi-square tests checking the distribution of self-incompatible plants (16 in P2) and non-self-incompatible plants (10 in P2) against the expectations of the original P1 population (61 SI plants, 0 non-SI plants) showed highly significant values for the asymptotic p-value of 0.000 and $\chi^2 = 2346141.54$ (Table 4). Also the studentized residuals of −10 for SI plants in P2 and of 10 for non SI plants in P2

**Table 3.** Student-Newman-Keuls post hoc tests for SI development of cultivars over P1 and P2. Mean values of homogeneous groups in subgroups are displayed, α = 0.05. Value 1.00 indicates 100% SI of the respective group, value 0.00 indicates 0.00% SI.

| Cultivar | N | Subgroups |
|----------|---|-----------|
|          |   | 1 | 2 |
| GER      | 3 | 0.33 |
| PRO      | 3 | 0.67 |
| HUN      | 20| 0.85 |
| DEG      | 54| 0.93 |
| LUT      | 7 | 1.00 |

**Table 4.** Results of chi-square-tests (Pearson), displaying asymptotic significance (p-value) and chi-square-value ($\chi^2$-value) to reveal differences of observed and expected SI distribution in respective populations.

| Observed distribution of SI in | Against the expectation of |
|-------------------------------|---------------------------|
| P-value | $\chi^2$-value | P-value | $\chi^2$-value |
| P1     | (78% SI, 22% non SI) | F1 after SI × SI | <0.001* | 168371.89 |
|        | Mean values of F1 total | F1 after SI × SI | <0.001* | 42352.50 |
|        |                          | F1 after SI × NSI | <0.001* | 243984.00 |
| P2     |                          | P2 | <0.001* | 2346141.54 |

* Significant at a level of error probability of α = 0.05.
show a highly significant decrease of SI occurrence and a highly significant increase of non SI plants in the course of time. These results indicate a strong influence of environment on SI development, maybe stronger than genetic influence. Yet, some cultivars exhibit more stable SI maintenance (‘Degumille’, mean 0.93) than others (‘Germania’, mean 0.33, or ‘Promyky’, mean 0.67).

Influence of generation—comparison of P1 and F1

In this research approach the situation is more complex because three crossing versions (SI × SI, SI × NSI, NSI × SI) act besides cultivars and generation as additional influencing factors. Distribution of SI development and number of plants in all cultivars and test populations can be checked in Table 1. Noticeable is the general high number of ‘Degumille’ plants in all variants, revealing a strong vigor and robustness of this cultivar. Per univariat two-way analysis of variance the SI development was checked taking into account the influencing factors ‘generation/crossing’ with the mean values of P1, F1 after SI × SI, F1 after SI × NSI and F1 after NSI × SI and the ‘cultivar’. Cultivar does not show any effect, but effects of generation/crossing are highly significant (p = 0.001, Table 1). No influence of interactions between cultivar and generation/crossing on SI development is identifiable (p = 0.207, Table 2). Exploring post hoc tests of the generation/crossing versions, the F1 generation after SI × NSI with the mean value of 0.86 exhibits the closest value to the 100% SI of the P1 generation and can be found in the same subgroup (Table 1). By looking at the results over all cultivars and generation/crossing versions again ‘Degumille’ with the F1 version of SI × NSI attracts attention by developing the highest value (0.86, Table 1) of SI. Therefore analysis of variance for all generation/crossing versions was conducted for ‘Degumille’ only and showed significant results (p = 0.007, Table 1). Apparently, ‘Degumille’, with self-incompatible mother plants crossed with non-self-incompatible father plants provides the best option to keep SI over generations.

Considering the distribution of SI and non SI plants in the different crossing combinations and comparing by chi-square-test with the expected distribution of the parental generation (P1; 61 SI and 0 non SI plants), a highly significant asymptotic deviation (p < 0.001) occurs for all crossing variations. χ² is 168371.89 for SI × SI, 42352.50 for SI × NSI and 243984.00 for NSI × SI (Table 4). Studentized residues show –/+ 14, –/+ 5 and –/+ 12 for SI and non SI plants in F1 after SI × SI, after SI × NSI and after NSI × SI, respectively, and therefore indicate a highly significant deviation of the 100% SI—population P1.

Statistically comparing the mean values of P1 and F1 total a highly significant effect of generation is displayed (p = 0.004, Table 2), whereas the effect of cultivar and interactions, respectively, show no influence (p = 0.282 and p = 0.126, resp.). However, it seems clear that in general there will be a lessening of SI abundance from the P1 to the F1 generation. The question is rather, if and how there is a difference of SI distribution between the different crossing variations of the F1, because—in case of genetic determination of the trait—paths of heredity and in consequence preferable ways of breeding could be revealed. Due to the high number of SI × SI progenies and consecutively high number of SI plants in this population a significant distinction of SI × SI against the other F1 populations seems probable (Fig. 1). But chi-square-tests (Pearson) after generated cross tables of the SI/non SI distribution in F1 populations and against the expectation of the mean values of these populations show an asymptotic p-value of 0.115 and χ² = 4.327. Therefore no oriented distinctness can be stated (Table 4). Even the two way analysis of variance shows no influence of cultivar or crossing version on SI occurrence (Table 2).

Influence of maintaining method—comparison of P2 and F1

The phenotypic appearance of a trait depends on genetics, on the environment and on interactions between both (Falconer 1984). To weigh the impact of environment and genetic heredity on SI development, starting from a general 100% SI test group (P1), the comparison of P2 and of F1 can give valuable information. As the percentages of SI in P2 displayed 62%, and in F1 total 78%, the assumption of higher impact of environment than of genetic determination on loss of SI is self-evident (Table 1). But one-way analysis of variance, exploring the effect of environment vs. generation, revealed these differences in SI occurrence not to be
significant. Calculated over all cultivars p-value exhibited 0.067, calculated for ‘Degumille’ only p-value was 0.600. However, the cultivar ‘Degumille’, displayed with 75% SI in P2 and 81% SI in F1 total the highest values of all cultivars (Table 1) ‘Degumille’ indicates thereby a high genetic stability and is worth a closer look.

**Influence of genetics—calculations of heritability**

This naturally leads to calculations of heritability of SI over generations. Broad sense heritability estimates how far variability of a phenotypic trait in a population depends on genetic differences (Becker 1993, Falconer 1984, Wricke and Weber 1986). As we specifically selected SI plants from a basic starting population and then crossed within this selected fraction (SI × SI), heritability of SI occurrence can be estimated. Realized heritability ($h^2$) in general is described as the response to selection (R) relative to the strength of selection (S) (Becker 1993, Falconer 1984, Wricke and Weber 1986). $h^2 = R/S$ and the values displayed in Table 1, $h^2$ of SI development displays the value 0.71 over all cultivars and 0.66 for ‘Degumille’. These values exhibit a genetic determination of 71% and 66%, respectively, of the phenotypic trait of SI in German chamomile.

**Discussion**

For breeding purposes self-incompatibility in hermaphroditic plants is a desired trait. To maintain once assessed self-incompatibility, two ways—vegetative and generative maintenance—seem possible. As a general outcome of this study an intra-cultivar, generative maintenance of self-incompatibility with the cultivar ‘Degumille’, using defined SI plants as mother and normal, not SI evaluated plants as father, can be recommended.

Reasons for this recommendation can be found on several levels of breeding efforts, e.g. in the practical fact that it will be easier to maintain a specific breeding line of annual and hapaxanth plants like German chamomile by generating successions of generations instead of recurrently producing vegetative cuttings of the same genetic material (Arbury et al. 1997, Bareja 2010, Guse and Larsen 2001). Moreover, the influence of environment on SI development can be high ($p < 0.001$). To exactly reveal the mechanisms of environmental influence of SI in German chamomile further investigations, including molecular biology and gene expression would be necessary, like Sijaic et al. (2004) and Thomann et al. (2015) showed for other plants.

Moreover, the high general heritability of SI in German chamomile ($h^2 = 0.71$) is notable. Commonly $h^2$-values over 0.6 are stated as a high heritability (Dorfman 2001). In previous investigations of intrinsic chamomile traits (essential oil compounds) equally high values of heritability (0.72–0.95) were discovered (Franz 1993). High co-heritability, as a description of genetic association within pairs of quantitative traits and a sign for low genetic variability and high inheritance (Janssens 1979), was discovered for a number of economic traits in German chamomile, like for fresh flower yield and for spread area (Lal et al. 2000). For breeding purposes, in particular, the heritability of reproductive traits in plants is an important and is therefore often investigated value. Moghe and Shiu (2014), for example, discovered significant genetic influence for the inheritance of unreduced gamete formation in crops. Whereas Austen et al. (2015) balanced heritability and environmental influence on sex allocation in hermaphroditic plants. The present work seems to be the first one investigating heritability values of reproductive traits in German chamomile.

Another remarkable finding is the co-occurrence of the SI × NSI crossing version and the P1 in the same subgroup after post hoc tests of analysis of variance for the influence of generation/crossing versions on SI development ($p = 0.001$), which shows the high affinity of this special crossing version to develop towards 100% SI in the P1 population. No statistical significance between crossing versions to guarantee the best maternally or paternally dominated crossing version can be provided ($p = 0.257$), but the above mentioned fact stresses the proximity of the crossing version SI (mother) × NSI (father) to the pure SI starting population and therefore serves as trend indicator for the best crossing version.

The outstanding features of the cultivar ‘Degumille’, exhibiting high SI stability over varying environments (mean value 0.93 over P1 and P2) and vigorous plants throughout the experiment, support the set up recommendation. Additional investigations to test interspecific but diploid crossing lines with ‘Degumille’ SI mother plants to find out ideal SI maintainer lines are a valuable future approach. Also to extend SI investigations to the tetraploid cultivar ‘Manzana’, an autopolyploid enhancement of ‘Degumille’, could be a reasonable approach, in particular to combine specific, desired reproductive traits like SI with economic interests of high drug yield and other useful characteristics (Franke et al. 2005).

**Acknowledgements**

This work was partly funded by the Fachagentur Nachwachsende Rohstoffe (FNR) of the Federal Ministry of Food and Agriculture, (BMELV), Germany, under the grant number 22038911.

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