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Impact of local heat leakage on vegetation and participation of non-native species

Master thesis

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Annotation:

Human-induced climate change is a recent phenomenon affecting vegetation structure and functioning. As a proxy of climate change, impact of long-term heat leakage from an underground pipeline on vegetation structure was investigated during a two-year study. Zone above the pipeline was considered as a heat island for non-native, potentially invasive plant species. To test this hypothesis, comparative field and laboratory germination experiments were conducted on closely related invasive and native species. Results of this study provide further evidence that climate change can alter vegetation composition and support invasion of non-native, especially C₄ species.

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1. Introduction

Reconstructions of the past millennium climate showed that Earth is anomalously warming from latter 20th century (Mann *et al.* 1999). This observed trend was suggested to exceed the bounds of natural variation (Mann *et al.* 1999; Karl & Trenberth 2003). Although Earth's climate has been naturally fluctuating during its whole history, recent human activities affect it significantly (Karl & Trenberth 2003; Root *et al.* 2005; Huber & Knutti 2011). Greenhouse gases released by human activities to atmosphere trap radiation outgoing from Earth to space and contribute to climate warming. Global mean surface air temperature increased about 0.6 °C per last 30 years (Hansen *et al.* 2006) and this increasing is predicted to continue (Williams *et al.* 2007). By the end of 21st century, mean air temperature can be 1.1–6.4 °C higher relative to the end of 20th century (IPCC 2007). However, Karlén (2005) pointed out that elevated temperature was not observed at several colder areas and that evaluation of short-term observation of temperature can lead to misinterpretations.

Climate warming is related not only to the increase of temperature, but also to droughts (Hoerling *et al.* 2012; Lelieveld *et al.* 2012), rise of sea-level (Meysignac & Cazenave 2012; Kuhlbrodt & Gregory 2012), more frequent extreme events such as El Niño–Southern Oscillations, floods, tropical cyclones (Easterling 2000; Holmgren *et al.* 2001; Wigley 2009; Cai *et al.* 2012), and temperature anomalies (Hansen *et al.* 2012).

Numerous studies provide evidence corroborating climate warming-induced changes at various levels of biological organization (Walther *et al.* 2002; Root *et al.* 2003; Walther 2003; Parmesan & Yohe 2003; Parmesan 2006; Chen *et al.* 2011; Dossena *et al.* 2012; Lurgi *et al.* 2012). Composition and structure of communities and ecosystems, as well as species' phenology, physiology and distribution are undergoing dramatic changes (Hughes 2000; Sparks *et al.* 2000; Walther *et al.* 2002; Wilson *et al.* 2005; Parmesan 2006; Woodward *et al.* 2010; Saino *et al.* 2010; de Sassi & Tylianakis 2012; Sardans *et al.* 2012; Heath *et al.* 2012). Despite of these dramatic changes across various communities, some communities seem to be unaffected by changing climate (Prach *et al.* 2009; Daniëls *et al.* 2011).

Understanding mechanisms underlying these changes is crucial to predict potential of a species to keep pace with climate warming. According to Gienapp (2008), there are three ways how can a species deal with climate changes in order to avoid far-reaching extinctions. Affected species can stay on original locality and adjust to new conditions by

phenotypic plasticity (phenotypic response), adapt to new conditions by evolution (genetic response) or disperse to suitable habitats. Since all three ways are time-dependent and successful establishment is a critical point after dispersion to a new habitat (Savolainen & Pyhäjärvi 2007), the rate of climate change is crucial for species survival.

1.1 Phenotypic plasticity vs. genetic adaptation

A short-term climate warming might be overcome by phenotypic plasticity (Ghalambor *et al.* 2007). However, any response by phenotypic plasticity is limited to a restricted range of temperature. Beyond this range, phenotypic response cannot further mitigate negative effects of enhanced temperature and another response, genetic, has to be involved to prevent detrimental loss of fitness (Gardner *et al.* 2009). Genetic response is based on selection for favourable traits that enable long-term persistence of populations (Donnelly *et al.* 2012). A population persists if the rate of genetic adaptation evolved by selection is at least the same as the rate of climate warming (Bürger & Lynch 1995). Both evolutionary processes are critical for survival of populations facing rapid climate warming and especially for sedentary organisms (i.e. plants) with limited capacity to migrate (Donnelly *et al.* 2012; Zhu *et al.* 2012). However, even species able to respond to these processes are not entirely safe (Bradshaw & Holzapfel 2006), because other drivers of global change as invasions and landscape fragmentation can affect these evolutionary processes (Jump & Penuelas 2005; Hoffmann & Sgrò 2011).

Significant amount of literature has been recently devoted to reveal the occurrence and magnitude of evolutionary processes in species' responses to climate warming. Despite strong evidence available for phenotypic response to climate warming (Menzel *et al.* 2006; Vitasse *et al.* 2010), evidence for genetic response remains scarce (Réale *et al.* 2003; Bradshaw & Holzapfel 2006; Donnelly *et al.* 2012). Lack of latter can be caused by inappropriate method of detection, slow (undetectable) speed of the response, or lagging of the response in time (Gienapp *et al.* 2008; Merilä 2012). Separation of phenotypic and genetic components of the response is difficult, but important step for future predictions of susceptibility of species to climate warming (Gienapp *et al.* 2008; Gardner *et al.* 2009).

1.2 Dispersal to suitable habitats

Third way allowing a species to cope with changing climate is to disperse from original to new habitats. Parmesan (2006) emphasized crucial role of this response during Pleistocene

glaciations. Seed dispersal to suitable habitats depends on their availability (establishment limitation) and ability of species to reach suitable habitats (seed limitation) (Clark *et al.* 1998, 2007; Ehrlén & Eriksson 2000). Establishment limitation is determined by number and quality of available habitats (or microsites) suitable for germination, establishment and persistence of species (Clark *et al.* 1998; Juenger & Bergelson 2000). Post-dispersal abiotic factors (temperature, light, moisture, and disturbance), biotic processes (competition from established vegetation, predation, parasitism, and lack of mutualists), seed viability and senescence highly influence the outcome (Maron & Simms 1997; Orrock *et al.* 2006; Clark *et al.* 2007; Bruun 2010). On the other hand, seed limitation is determined by number of produced seeds (source limitation) and by their dispersal ability (dispersal limitation) (Clark *et al.* 2007).

Relative importance of both these limitations in shaping composition, abundance and distribution of plant species on a local-scale have been thoroughly discussed (Eriksson & Ehrlén 1992; Clark *et al.* 2007). Some studies demonstrated seed limitation (Primack & Miao 1992; Dalling *et al.* 2002; Rey *et al.* 2005; Ehrlén *et al.* 2006; Marsico & Hellmann 2009), while other reported establishment limitation (Crawley 1990; Turnbull *et al.* 1999; Hubbell 1999; Pearson *et al.* 2002). Recently, it was shown that both limitations can participate at once (Eriksson & Ehrlén 1992; Honnay *et al.* 1999; Ehrlén & Eriksson 2000; Dalling *et al.* 2002; Clark *et al.* 2007; Emery *et al.* 2009; Dullinger & Hu 2011) and that establishment limitation may be more important than ever thought (Tilman 1997; Zobel & Kalamees 2005; Zeiter *et al.* 2006).

1.3 Vulnerability of species to climate change

Several species have been shown to be unable to track changing climate (Primack & Miao 1992; Marsico & Hellmann 2009; Van der Veken *et al.* 2012; Zhu *et al.* 2012), which can, in turn, put them to high risk of extinction (Root *et al.* 2003; Thomas *et al.* 2004; Parmesan 2006). According to Broennimann *et al.* (2006), species' vulnerability is determined by its geographical distribution, niche breadth or proximity to barrier preventing migration, and can be *a priori* estimated. However, due to paucity of available knowledge about responses on species level, it is very challenging to assess vulnerability of individual species (Holt 1990; Broennimann *et al.* 2006; Hoffmann & Sgrò 2011). Incorporating this knowledge to new conservation strategies is critical to prevent or minimize extinction and loss of biodiversity (Root & Schneider 2006; Lawler *et al.* 2010).

One of proposed strategies (called assisted migration or colonization) suggests introduction of potentially endangered species beyond their historical range so that they will be able to survive under future climate (McLachlan *et al.* 2007). An outburst of controversy has arisen about the implementation of this strategy, because it carries, among others, risk of introducing potentially invasive species to new areas (Hoegh-Guldberg *et al.* 2008; Loss *et al.* 2011). Hoegh-Guldberg *et al.* (2008) emphasized the importance of thoroughly understanding the strategy before its implementation and botanical gardens were suggested as an ideal place for the strategy testing (Primack & Miller-Rushing 2009).

1.4 Experimental approaches for testing limitations

The most common approach testing relative importance of seed and establishment limitations is to perform a seed addition experiment (Turnbull *et al.* 2000, 2005; Clark *et al.* 2007, Table 1). According to Turnbull *et al.* (2000), there are two types of seed addition experiments. Seeds are either added to areas where the species normally grow (seed augmentation) or they are introduced to new areas (seed introduction). Evaluation of such experiments is hampered by drawbacks (Turnbull *et al.* 2000; Clark *et al.* 2007) and several authors pointed out misleading results coming from short-term observations (Zobel & Kalamees 2005; Ehrlén *et al.* 2006; Gaston 2009).

Seed introduction can be also implemented in studies predicting the potential of plant species to colonize new ranges (Mack 1996). Only small number of studies introduced seeds of target species beyond their distribution range for this purpose and most of them examined only a single species in a short-term experiment (Levin & Clay 1984; Andersen *et al.* 1985; Prince & Carter 1985; Van der Veken *et al.* 2007; Van der Veken *et al.* 2012). Mack (1996) suggested that combining seed introduction approach with other approaches, such as field manipulations of environment or comparison between closely-related congeners, will provide finest prediction. Comparisons between two congeneric species (non-native and native) can reveal shared traits and, more importantly, different traits which can be responsible for different performance in a new range (Mack 1996). This combined comparative approach has been incorporated only in few studies. Notably, it was recently implemented by Sheppard *et al.* (2012) to compare performance of non-native and native meadow species under conditions simulating climate change (extreme events and warming).

1.5 Objectives of study

Here, I take advantage of existence of underground steam pipeline system in České Budějovice (Czech Republic) to disentangle effects of soil temperature increase on vegetation and particularly on the occurrence of invasive species. During the two-year period, comparative approach was used to assess vegetation and temperature differences between the zone with heat leakage and heat non-affected control zone. To test if the pipeline zone can serve as a heat island where non-native thermophilic species can recruit and establish, invasive species were sown in a field experiment and compared to their non-invasive relatives.

Based on knowledge gained during my bachelor study of vegetation above the pipelines, I have decided to test following hypotheses:

- vegetation above the pipeline differs from surrounding vegetation
- short-lived plant species are widely represented above the pipeline
- non-native species are able to recruit and establish above the pipeline more easily than outside it

2. Materials and Methods

2.1 Study sites and experimental design

The experiment was carried out at three sites (designated as site 1, 2 and 3 hereafter) in České Budějovice (Czech Republic) from 25 June 2010 till 20 June 2012. All the study sites are located near each other (48°58'24"N, 14°27'28"E, 380 m a.s.l.) above the underground steam pipeline in the local park (Stromovka). The pipeline is formed by two pipes of different diameter size. The larger pipe conveys steam of approximately 180 °C and the smaller pipe conveys hot water of approximately 70 °C. The pipeline was built between the years 1982-1985 and is deposited on gravel ballast around 1.5 m underground.

Although all three sites are covered by mown lawns, only sites 1 and 2 are cut regularly and at the same time. Cutting starts in April or May and continues with a month period to November. Site 3 is cut from August 2011 only few times per a season. Fifteen 1×1 m plots were delimited at each site in three zones: five plots were established in the middle of the zone above steam pipeline (zone A), five plots were located half a meter from them (zone B, outside the pipeline) and five remaining plots were located fifteen meters apart from previous plots (zone C, Fig. 1). Zone A was determined using maps of the pipeline (provided by Teplárny České Budějovice, a.s.) and vegetation differences. The distance between each two adjacent plots in each of the three zones was three meters (Fig. 1). Percentage cover of all vascular plants was estimated in plots every two weeks in spring and summer and in the rest of the year monthly if possible (e.g. not covered by snow). Nomenclature of plant taxa, except *Galinsoga ciliata*, was used according to Kubát *et al.* (2002).

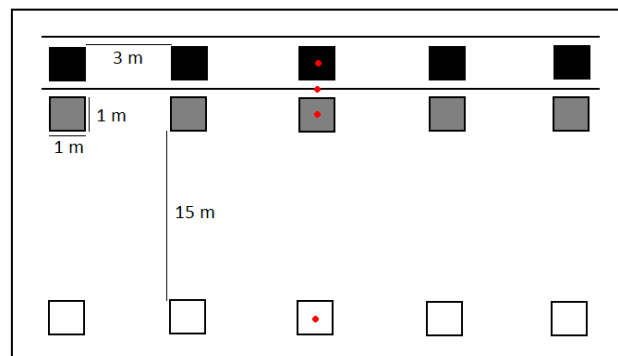


Fig. 1. Design of plots at each site. Zone A is represented by black squares, zone B by grey squares and zone C by white squares. Red points symbolize the locations of Minikin dataloggers.

Unfortunately, five C-plots at the second site were destroyed (covered by soil) in September 2010. Since data were sampled only five times from these plots, they were completely eliminated from any subsequent analyses to prevent potential biases.

2.2 Soil temperature and moisture measurements

Soil temperature was measured by twelve Minikin (EMS) and four TMS first generation (TOMST®) datalogger devices with an accuracy of 0.2 and 0.5 °C, respectively. At each site, four Minikin devices were buried a few centimeters underground as described below. The first was placed into the middle of the zone above steam pipeline (zone A), the second was placed into the middle of intermediate plot outside the zone (zone B), the third was placed between these two devices (in the transition zone, zone A-B) and the last was laid into the middle of the most remote plot (zone C, Fig. 1). Minikin dataloggers recorded temperature every 30 minutes from 7 July 2010 till 14 August 2012. TMS dataloggers were placed near already deposited Minikin devices to the second site and were primarily used to measure soil moisture every 30 minutes from 1 December 2011 till 30 November 2012.

Downloaded soil moisture data, expressed in arbitrary units, were converted to the percentage of volumetric water content using a calibration curve. Calibration of devices was done according to instructions in Vlček (2010). The following regression equation was obtained: $y = 0.00034x - 0.20754$, and the coefficient of determination $R^2 = 0.99848$ (Suppl. Mat. 1).

2.3 Sowing experiments

The ability of five chosen closely related species to germinate, survive and potentially reproduce in the zone above steam pipeline was examined by a field experiment. Simultaneously, a laboratory germination experiment was carried out to provide background knowledge about the influence of various temperatures on species germination. Phylogenetically closely related species from two distinct clades of Asteraceae were chosen for comparisons. Two native *Senecio* species (*S. jacobaea* and *S. viscosus*) were compared to non-native *Senecio inaequidens*, and non-native *Tridax procumbens* was compared to naturalized non-native *Galinsoga ciliata*.

2.3.1 Studied species

***Senecio inaequidens* DC. (narrow-leaved ragwort, South African ragwort)**

S. i. is a perennial herb reaching up to 1 m with original distribution in mountainous regions of Lesotho and South Africa (Hilliard 1977; Monty *et al.* 2010; Lachmuth *et al.* 2010). In its native range, it colonizes primary habitats such as rocky slopes, outcrops, and gravel banks, but it also grows in disturbed areas such as vineyards, roadsides, coastal dunes and heavily grazed grasses (Lafuma & Maurice 2007; Bossdorf *et al.* 2008; Caño *et al.* 2009).

By the end of the 19th century, the species was introduced into Europe. As all centers of early introduction (Bremen, Calais, Lüttich, Verona, Mazamet) were associated with wool trade, sheep wool is considered to be a source of seeds (Ernst 1998; EPPO 2006). Until 1950s, *S. inaequidens* was found only around existing wool-processing factories (Ernst 1998), but since then it has rapidly spread throughout western, central and southern Europe (Monty & Mahy 2010). In 1997, the species firstly reached the Czech Republic (Pyšek *et al.* 2012). It is assumed that a significant amount of seeds might be transported on long distances in the profile of tires (Heger & Böhmer 2006).

Not only human unintended assistance, but also several life-traits allowed *S. inaequidens* to become troublesome invasive species in Europe (Schmitz & Werner 2001). For example, its long flowering period enables the species to produce more than 100,000 achenes per an individual a year (Böhmer *et al.* 2001; López-García & Maillet 2005; Heger & Böhmer 2006). High outcrossing rate resulting from self-incompatibility can be other contributing factor explaining its high seed set (Vanparys 2011).

Although *S. inaequidens* invades mainly ruderal habitats in its secondary range, it has recently occurred in natural communities as dry grasslands (Bossdorf *et al.* 2008), pine forests and coastal dunes (Brunel 2003; Lachmuth *et al.* 2010). Noted as noxious weed at Mediterranean pastures, it can poison livestock because of its substantial level of pyrrolizidine alkaloids (Dimande *et al.* 2007). On the other hand, avoidance by grazing animals acts as competitive advantage further promoting its invasive features (Bossdorf *et al.* 2008).

***Senecio jacobaea* L. (ragwort, tansy ragwort)**

S. j. is a monocarpic perennial (rarely annual) commonly reaching about 50 cm in height. The plant usually forms a rosette during the first year of life and flowers in the following season (Wardle 1987; Parsons & Cuthbertson 2001). It reproduces both sexually and vegetatively (Poole & Cairns 1940). Because of the self-incompatibility of the species, sexual reproduction fully depends on insect pollinators (Andersson 2001). Produced achenes are distinguishable to two morphologic groups possessing different germination and dispersal abilities (McEvoy 1984; McEvoy & Cox 1987).

According to Sharrow *et al.* (1988), ragwort is native to Europe and western Asia (from Norway to Asia Minor and from Great Britain to Siberia) where it naturally colonizes open grasses, woodland communities and sand dunes, and can be also found in many human disturbed habitats (Harper & Wood 1957; Bain 1991). Although it is able to inhabit a broad range of habitats (Harper & Wood 1957), it prefers the mesic ones (Bain 1991). Nowadays, it is regarded as a pasture weed in many temperate areas (Australia, New Zealand, South Africa, South and North Americas) into which it was introduced in the 19th century (Wardle *et al.* 1995; Parsons & Cuthbertson 2001). As it contains pyrrolizidine alkaloids similarly as *S. inaequidens*, a lot of attention has been paid to the control of this species (McEvoy *et al.* 1989; Bain 1991; Crider 2011).

***Senecio viscosus* L. (sticky groundsel, sticky ragwort)**

S. v. is an annual early-flowering herb capable of self-fertilization (Warwick *et al.* 1978). It was primarily distributed around temperate Asia and Europe (except the northern part) across various habitats containing rocky slopes, open forest, sandy or gravelly places, and wastelands (Hegi 1987). Later, the species was introduced to northern Europe, United States, and Canada where it become naturalized.

***Tridax procumbens* L. (coat button, tridax daisy)**

T. p. is an annual or short-lived perennial originally native to Central and tropical South America and the West Indies, but now widespread all over the tropical and semi-tropical latitudes (West Africa, Southeast Asia, and Philippines). In the secondary range, the species predominantly colonizes arable land, but it also grows along railroads, roadsides, waste grounds, dikes, riverbanks, dunes and meadows. Subsequent dispersal to colder

latitudes may be limited by high temperature required for germination (Chauhan & Johnson 2008).

As a successful weed, coat button produces high amount of seeds or rapidly spreading stems (Baker 1965) and negatively affects surrounding vegetation by allelopathy (Holm *et al.* 1997). Its effects notably decrease crop yields and so it is listed as a noxious weed that has to be regulated (USDA 2010). Ipou *et al.* (2011) suggested annual leguminous plants to control the species in cotton culture in the North of Ivory Coast.

Despite the previous facts, *T. procumbens* is also used as a medicinal plant with antibacterial activity and capacity to heal wounds and stop bleeding (Samy *et al.* 1999; Kumar *et al.* 2007).

***Galinsoga ciliata* Raf. (hairy galinsoga, shaggy soldier)**

G. c. is an annual herb closely related to *T. procumbens* (Watson *et al.* 1991; Bergquist *et al.* 1992) and resembles it in many characteristics such as appearance, place of origin and reproductive traits.

Original distribution of hairy galinsoga is in South and Central America (from Chile to Mexico) and it was introduced to most temperate and subtropical areas of the world (Sweet 1986; Kabuce & Priede 2010; Kosaka *et al.* 2010). Important pathways of its invasion in Europe include escaped individuals from botanical gardens, contamination of soil or seeds of ornamental plants, and transport vehicles. *G. ciliata* is considered as weedy plant naturalized in many European countries (Kabuce & Priede 2010). In its primary and secondary range, it grows particularly in urban areas in gardens, greenhouses, cultivated fields, roadsides, railways and dump sites (Kabuce & Priede 2010), but it was also recorded by Chmura (2004) from semi-natural woodlands.

2.3.2 Seed sources

Seeds of studied species were acquired from several distinct sources by the author if not stated otherwise. Seeds of *S. inaequidens* and *S. viscosus* were collected at the Bubny railway-station in Prague (50°6'5"N, 14°26'25"E) in December 2011. Seeds of *S. jacobaea* were obtained from a commercial company [<http://www.plantanaturalis.com>]. Seeds of *Galinsoga ciliata* were gathered at Vlášence (49°27'56"N, 14°33'58"E) in 2009. Nevertheless, their amount was insufficient for further experiments. Therefore, collected seeds of *Galinsoga ciliata* were sown on surface of moist soil consisting of garden

substrate (Agro CS a.s.) and sand (1:1) and plants were exposed to 15–30 °C in a greenhouse in spring 2011. Sufficient amount of ripe seeds was then harvested and stored for experiments. Seeds of *Tridax procumbens* produced in different years (1-3 years old) were provided by Prague Botanic Garden.

2.3.3 Preliminary examination of germination rate

The germination rate of studied species was verified in constant conditions before the start of main experiments. Seeds of *Senecio* species (100 seeds per species), *G. ciliata* (50 seeds) and *T. procumbens* (50 seeds) were planted out on moist soil (1 part of garden substrate: 1 part of sand) and kept in 21 °C, 16 hours of light a day. Number of emerged individuals was recorded once per 1–6 days for each species. Examination of germination rate was ended after one month.

2.3.4 Laboratory germination along a temperature gradient

Seed germination response was investigated by exposing seeds of studied species to a temperature gradient (0–32 °C). On 3 May 2012, 25 six-well culture plates were distributed across the gradient in five rows (1-5) and five columns (A-E). Seeds were randomly divided into wells except that there were always same species placed to two 3-well lines in a column (Suppl. Mat. 2). Exact number of seeds (15) was placed into each well on filter paper, watered by 500 µl of tapped water and plates were covered with plastic wrap and lid. Water has been constantly supplied and number of germinated seeds has been counted every 1–3 days for one month. Finally, temperatures in corners of every plate (36 positions) and positions of plates on the gradient table were measured.

2.3.5 Field sowing experiment

Experimental site consisted of 30 1×1 m plots (ten plots with three replications). Fifteen plots were situated within the zone above steam pipeline (zone A) and the rest was set up sixteen meters farther (zone C, close to most remote vegetation plots). Every plot comprised five subplots (25×25 cm in size), from which aboveground and belowground (the upper five centimeters) biomass was removed before sowing. Randomized experimental design was used so that every subplot contained seeds of random species and every plot contained all five species.

On 4 May 2012, seeds were scattered on a topsoil in the centers (10×10 cm) of subplots and moderately watered. Exactly 100 seeds of *Senecio* species and 50 seeds of *Galinsoga* and *Tridax* species were dispersed per subplot. Numbers of emerged seedlings and established plants were recorded once per 6–12 days and subplots were weeded weekly. Sometimes individuals of one species emerged in a plot determined to another species. They were removed when they visibly inhibited original species.

Timing of phenological events such as emergence of first buds or flowers and survival of studied species was observed and recorded in both zones.

2.3.6 Seed viability of *Tridax procumbens*

Mature seeds of *T. procumbens*, collected from zones A and B, were separately counted and 200 seeds from every zone (2×200) were used for further examination. One quarter of seeds (2×50 seeds) was tested for germination rate in a laboratory as described previously (see paragraph *Examination of germination rate*). Three quarters of seeds (2×150 seeds) were sown back to subplots on 27 November 2012. From ten A-subplots, five A-subplots received 15 seeds collected from A-subplots (5×15), and the other five A-subplots received 15 seeds collected from C-subplots (5×15). Ten C-subplots were treated identically as A-subplots.

2.4 Data Analyses

2.4.1 Vegetation data analyses

All analyses were performed and visualized in Canoco 5, Windows release 5.0 (Ter Braak & Šmilauer 2012). Species data were logarithmically transformed [$y' = \log(1*y + 1)$] and the weight of rare species was decreased during every analysis (Lepš & Šmilauer 2003).

2.4.1.1 Multiple sites analyses

All obtained data were tested at once by Detrended Correspondence Analysis (DCA) for any seasonal dynamics of plants occurring in zone A, B, or C. Subsequently, Canonical Correspondence Analysis (CCA) was conducted to evaluate how much data variation was explained by presence or absence of the pipeline. Since the number of plots at the second site was not consistent with other sites, neither permutation tests nor hierarchical design was implemented.

Moreover, the permutation test in CCA could not be initiated with restriction to two sites because there were two zero samples in data. A Distance-based Redundancy Analysis (RDA; Legendre & Anderson 1999) had to be added using Gower distance measure for calculating relevé distances and position of plots (A, B, C) as explanatory variables. Plant species were projected as supplementary data and a hierarchical design with one observation indicating a split-plot and a site representing a whole-plot was set up. A Monte-Carlo permutation test with 499 permutations was executed at a 0.05 level of significance.

2.4.1.2 Single sites analyses

Data from each site were analyzed independently by DCA, CCA and Distance-based RDA. One zero-sample was present in all data sets, so application of Distance-based RDA was inevitable. Constrained ordination diagrams were created by CCA, but significance level was calculated by Distance-based RDA.

2.4.2 Laboratory germination analyses

Coordinates of plates on the gradient table and corresponding measured temperature values were analyzed by a loess model (with span parameter set to 1/3; Fig. 2, Fig. 3) to obtain interpolated temperature values for each well. Relating these temperatures and total

proportion of germinated seeds by a Generalized Linear Model (GLM) with quasibinomial distribution provided an estimate of optimum temperatures for species germination. Another GLM with quasibinomial distribution was used to estimate germination rates of the studied species. All analyses were conducted in R, version 2.15 (R Development Core Team, 2012).

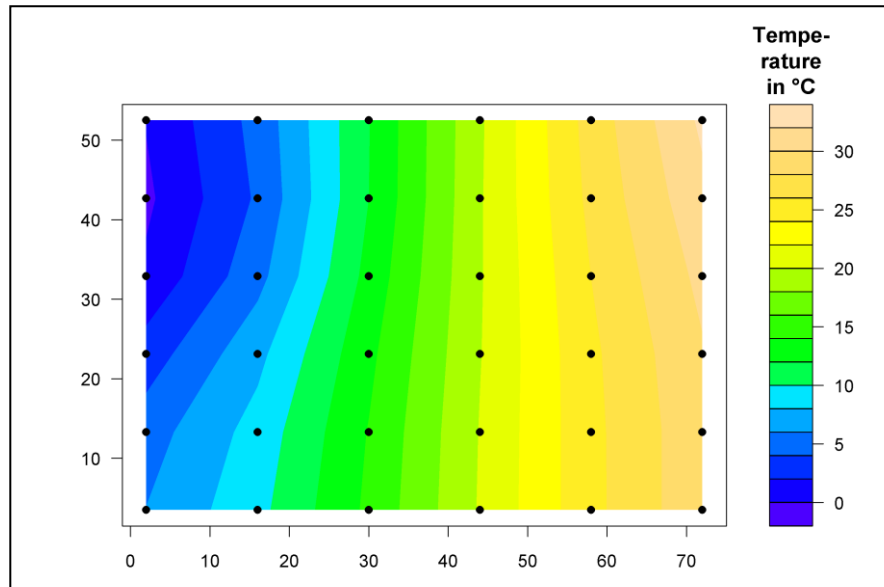


Fig. 2. Temperature gradient fitted by the loess model. Points represent the places, where temperature was measured.

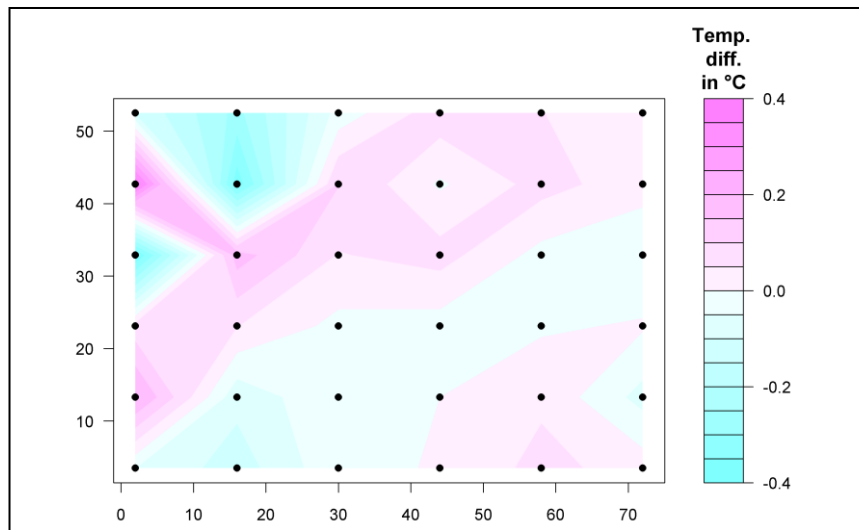


Fig. 3. Temperature differences (°C) between actual measured and model-fitted values. The maximal difference between the loess model fit and actual measured values was 0.4 °C.

2.4.3 Field sowing analyses

Observed numbers of germinated seeds were also analysed by GLM with quasibinomial distribution in R, version 2.15 (R Development Core Team, 2012).

3. Results

3.1 Vegetation data

During the two-year observation of study plots, 69 plant species were recorded in 990 phytosociological relevés. Site 1 contained 46 species and 42 species were found at site 2 and 3. I distinguished 26 non-native species: 20 neophytes and 6 archaeophytes. Raw vegetation data are available at petra.svetlikova@seznam.cz.

3.2 Vegetation data analyses

3.2.1 Multiple sites analyses

Testing all the sites together by Detrended Correspondence Analysis (DCA, Fig. 4) showed more apparent seasonal changes of vegetation in zone A than in zones B and C. Differences between sites suggest separation of the third site indicating dissimilarity between this site and other sites (Fig. 4). The continuous transition from zone A to zone C is noticeable (Fig. 4). First and second canonical axes explained 14.2 and 9.0% of variation.

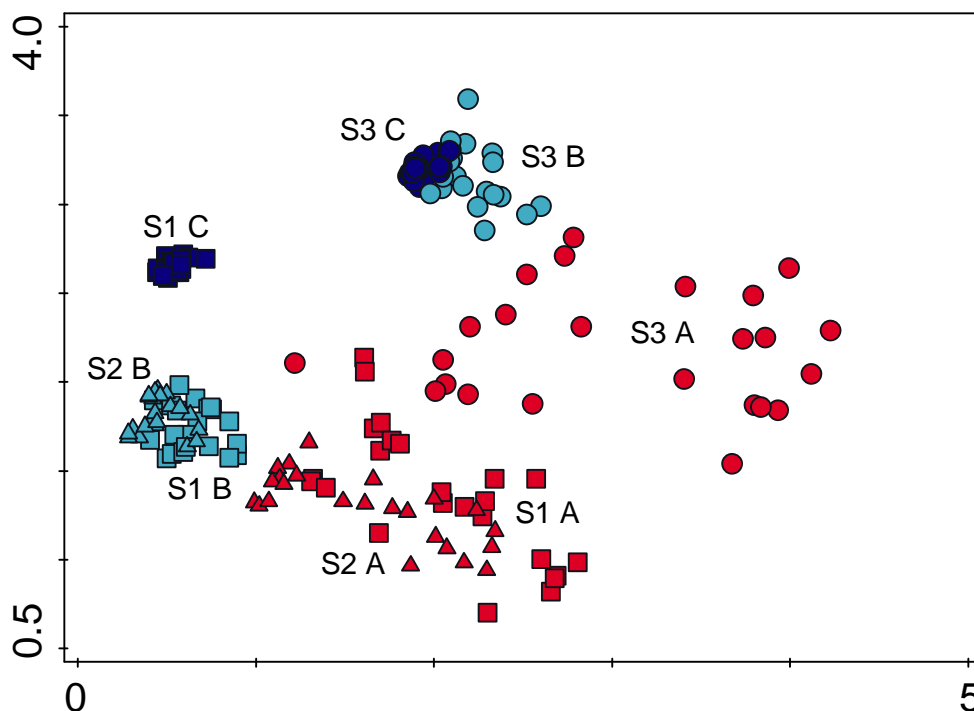


Fig. 4. Unconstrained ordination method (DCA) showing seasonal changes of vegetation at the three study sites (S1-S3) during two years (June 2010 – June 2012). Symbols in red correspond to the pipeline zone (A), -symbols in light-blue to plots 0.5 meters outside the zone (B) and symbols in dark-blue to the most distant plots (C). The first site is presented by squares, the second site by triangles and the third site by circles. Each symbol denotes to the composition of vegetation in five plots during one observation time (centroids used).

The position of observed species and the participation of non-native species especially in the zone A (right bottom) are derived from the same analysis (Fig. 5).

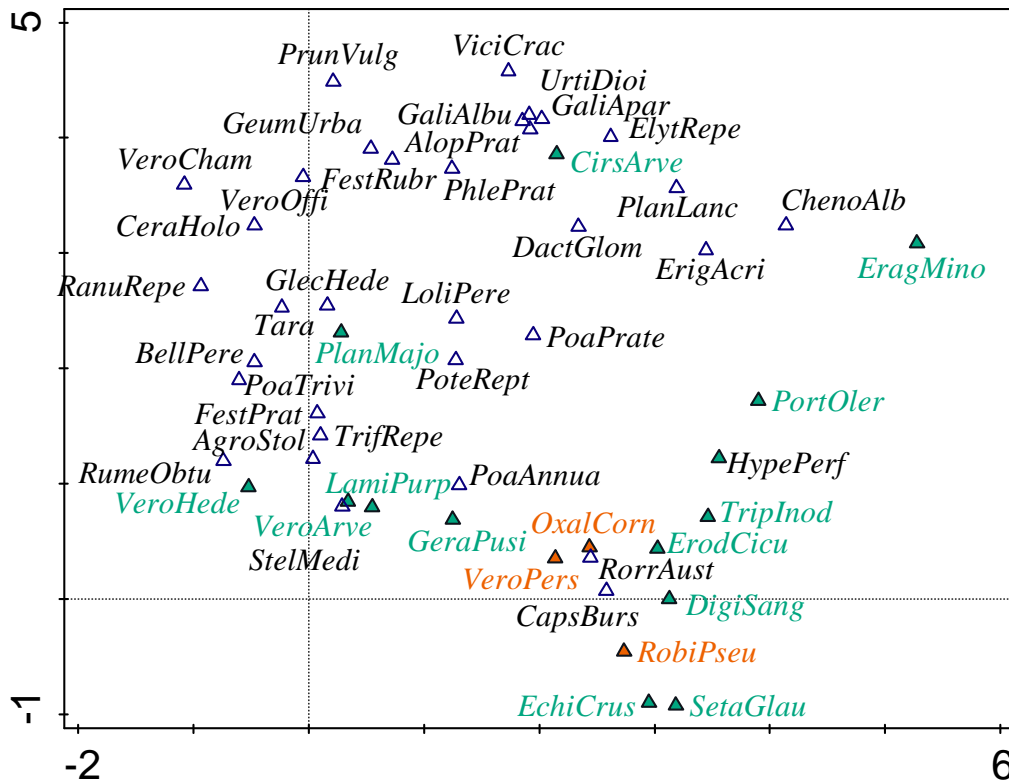


Fig. 5. Unconstrained ordination method (DCA) displaying positions of 50 plant species with largest weight. Non-native species are highlighted, neophytes by orange colour and archaeophytes by green colour. Abbreviations are explained in Supplementary Material 3.

Canonical Correspondence Analysis (CCA) covering all three sites (Fig. 6) or only sites 1 and 2 (Fig. 7) implies usual habitat of species with regard to zones A, B and C. First and second canonical axes accounted for 6.3 and 3.8% of variation of all-sites dataset, while first and second canonical axes explained 9.3 and 4.1% of variation of two-site dataset. Zones are equally distributed from each other (Fig. 6, 7). Although zones A and B have many species in common, almost no species occur in zone A and C at the same time (Fig 6, 7).

Distance-based RDA diagrams inferred from all three datasets or from first and third datasets are not shown, but both axes in both analyses explained more variability than in CCA. First and second canonical axes accounted for 7.3 and 6.3% of variation of all-sites dataset, while first and second canonical axes explained 9.9 and 6.1% of variation of two-site dataset. Permutation test with three explanatory variables (A, B, C) conducted

only for data from site 1 and 3 is significant ($P = 0.002$) suggesting that vegetation of these three zones is significantly different.

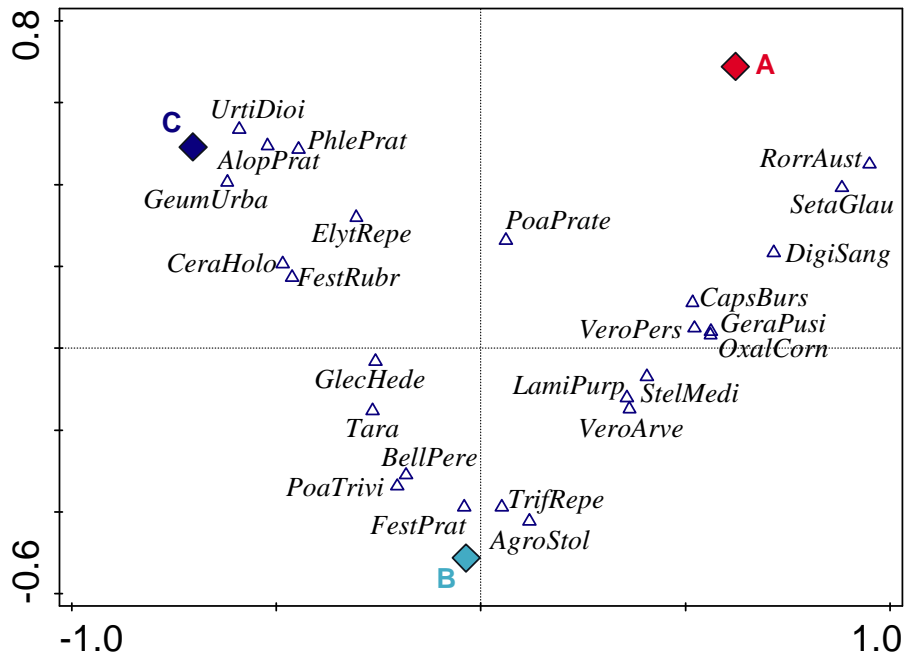


Fig. 6. Constrained ordination method (CCA) including all data and indicating preferences of 25 best fitted plant species for the pipeline zone (A) or for the outside the zone (B, C). Abbreviations are explained in Supplementary Material 3.

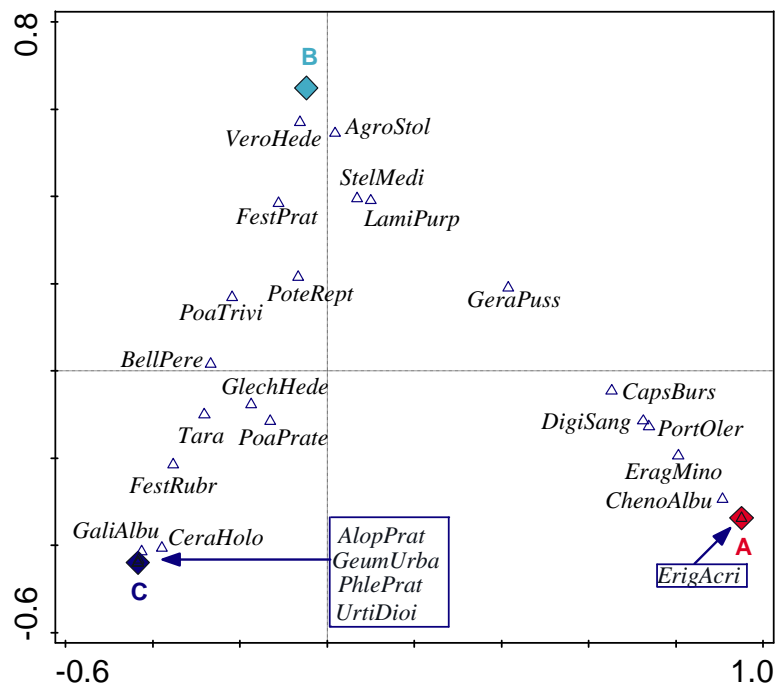


Fig. 7. Constrained ordination method (CCA) including only the first and the third sites and indicating preferences of 25 best fitting plant species for the pipeline zone (A) or for the outside the zone (B, C). Abbreviations are explained in Supplementary Material 3.

3.2.2 Single sites analyses

Site 1

Detrended Correspondence Analysis (DCA) presents seasonal dynamics of vegetation at the first site and demonstrates decreasing amount of changes in vegetation during a year from the zone A to the zone C (Fig. 8). First and second canonical axes explained 20.9 and 9.6% of variation.

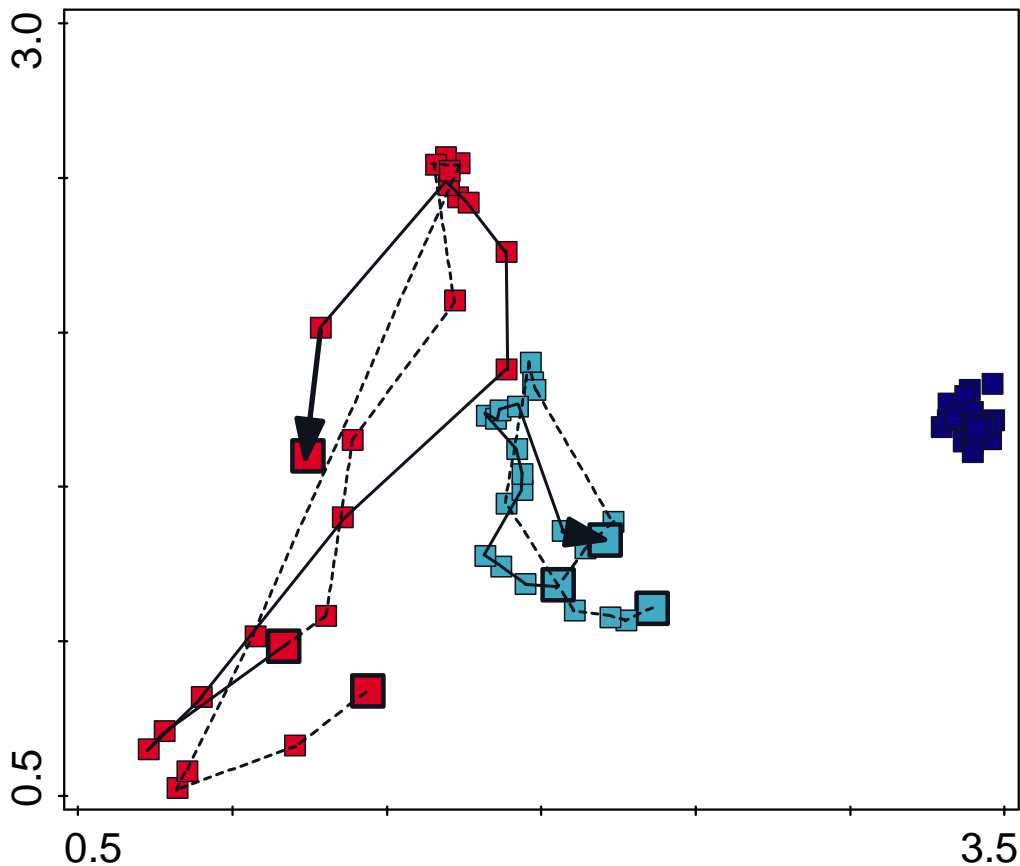


Fig. 8. Seasonal dynamics of vegetation at the first site during two years obtained by unconstrained ordination method (DCA). Symbols in red correspond to the pipelines zone (A), symbols in light-blue to plots 0.5 meters outside the zone (B) and symbols in dark-blue to the most distant plots (C). Every symbol (centroid) denotes to the composition of vegetation in five plots during one observation time. Dashed line indicates first year and solid line indicates second year. Enlarged symbols represent first (June 2010), intermediate (June 2011), and last (June 2012) observations. Arrows show last observations.

Preferences of species for zone A, B or C are shown on constrained unimodal ordination (CCA) diagram (Fig. 9). While within site 1, *Portulaca oleracea* and *Digitalia sanguinalis* grew predominantly in the zone A, *Dactylis glomerata*, *Veronica hederifolia*, and *Agrostis stolonifera* preferred places near the zone A, and *Lolium perenne*,

Taraxacum sp., and *Cerastium holosteoides* occurred farther from it (Fig. 9). First and second canonical axes explained 16.9 and 10.7% of variation.

From Distance-based RDA, first and second canonical axes accounted for 25.2 and 14.5% of variation. Species composition of individual zones is significantly different ($P = 0.002$).

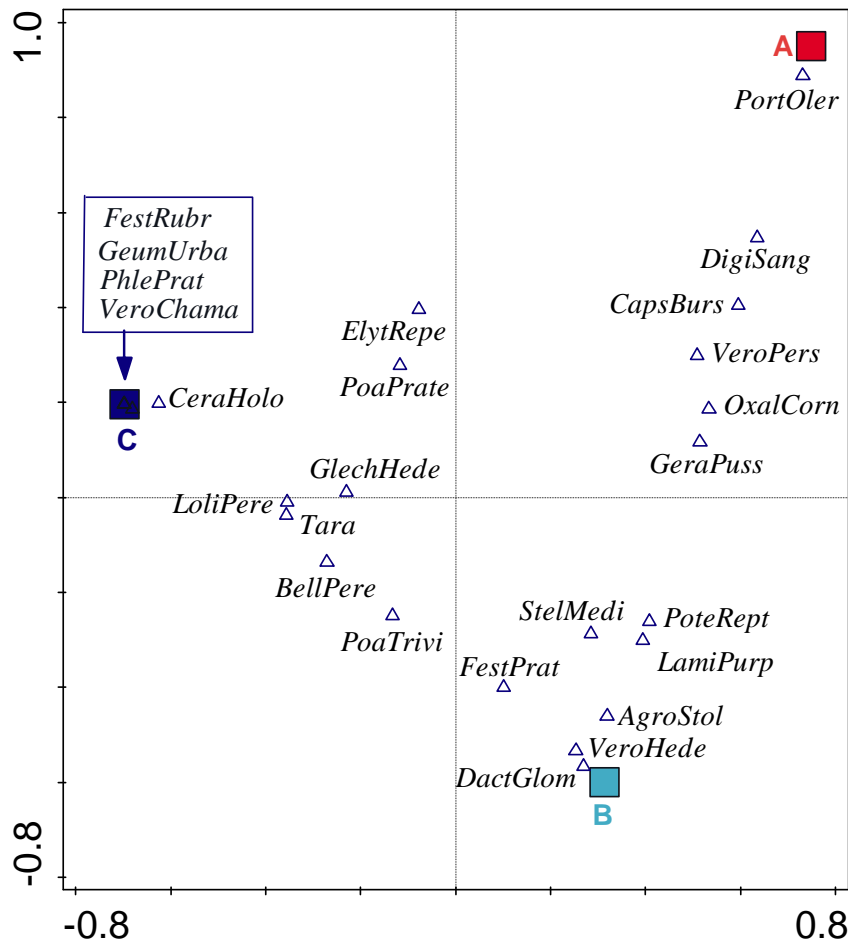


Fig. 9. Constrained unimodal ordination diagram (CCA) representing relationships of 25 best fitted plant species to the pipeline zone (A) or the outside zones (B, C). Abbreviations are explained in Supplementary Material 3.

Site 2

Vegetation at the second site was changing quite rapidly in the zone A when compared to the zone B (Fig. 10). First and second canonical axes of DCA accounted for 22.7 and 9.9% of variation.

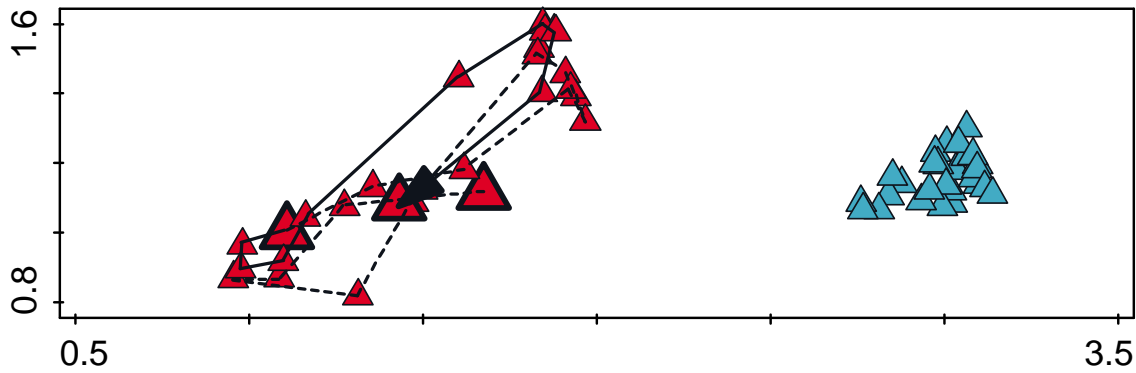


Fig. 10. Seasonal dynamics of vegetation at the second site during two years obtained by unconstrained ordination method (DCA). Symbols in red correspond to the pipelines zone (A) and symbols in light-blue to plots 0.5 meters outside the zone (B). Every symbol (centroid) denotes to the composition of vegetation in five plots during one observation time. Dashed line indicates first year and the solid line indicates second year. Enlarged symbols represent first (June 2010), intermediate (June 2011), and last (June 2012) observations. Arrow shows last observation.

Canonical Correspondence Analysis (CCA) of data from the second site shows preferences of *Rorripa austriaca*, and *Geranium pusillum* for the zone A and preferences of *Poa trivialis*, *Glechoma hederacea* and *Plantago major* for the zone B (Fig. 11). First canonical axis accounted for 18.1% of variation.

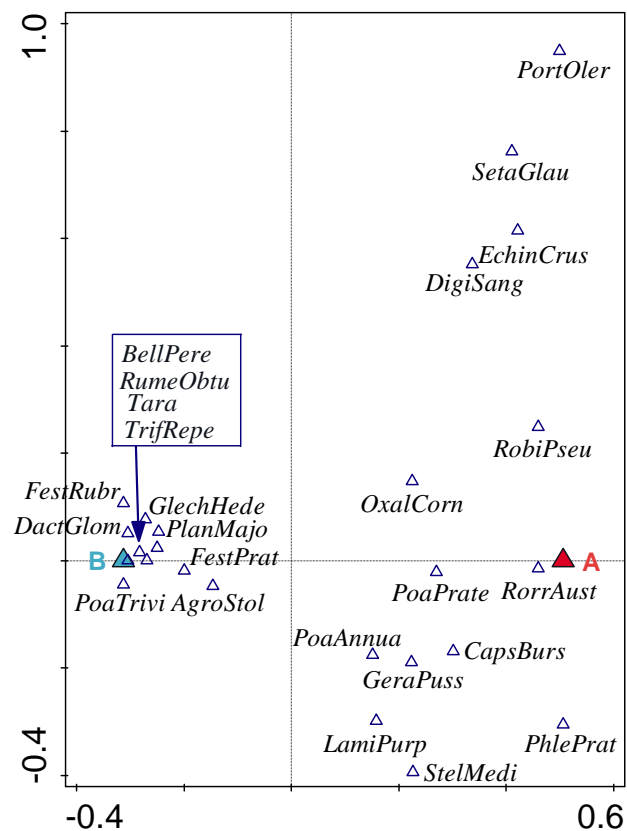


Fig. 11. Constrained unimodal ordination diagram (CCA) representing relationships of 25 best fitted plant species to the pipeline zone (A) or the outside zone (B) at the second site. Abbreviations are explained in Supplementary Material 3.

Same explanatory variables used in Distance-based RDA with hierarchical design explained 24.64% of variation and the vegetation of the zone A is significantly different from the zone B ($P = 0.01$).

Site 3

Already described trend of greater changes of vegetation in the zone A was also evident at the third site (Fig. 12). First and second canonical axes within the DCA explained 22.4 and 10.9% of variation.

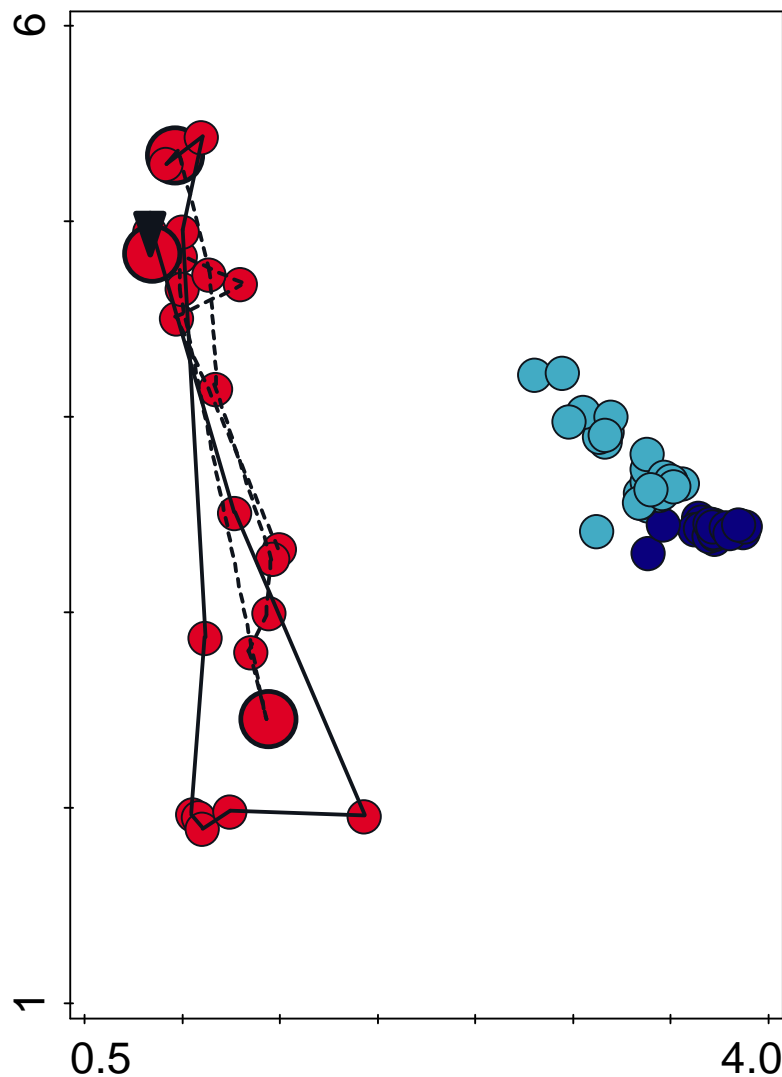


Fig. 12. Seasonal dynamics of vegetation at the third site during two years obtained by unconstrained ordination method (DCA). Symbols in red correspond to the pipelines zone (A), symbols in light-blue to plots 0.5 meters outside the zone (B) and symbols in dark-blue to the most distant plots (C). Every symbol (centroid) denotes to the composition of vegetation in five plots during one observation time. Dashed line indicates first year and the solid line indicates second year. Enlarged symbols represent first (June 2010), intermediate (June 2011), and last (June 2012) observations. Arrow show last observation.

According to the CCA of dataset from the third site, *Tripleurospermum inodorum*, *Erigeron acris*, *Plantago lanceolata*, and *Digitaria sanguinalis* can be considered as typical species for the zone A, whereas *Galium album*, *Aloperurus pratensis*, *Cirsium arvense*, and *Phleum pratense* occurred predominantly in the zone B (Fig. 13). Many species were common for zones B and C (Fig. 13). First and second canonical axes accounted for 19.9 and 3.9% of variation.

Although Distance-based RDA explained much more variability than CCA (31.1% vs. 23.7%), most of variability was explained by first canonical axis (31.3% for first as opposed to 1.8% for second axis) suggesting more dissimilarity between zones A and B than between B and C. The composition of vegetation significantly differed between these three zones ($P = 0,002$).

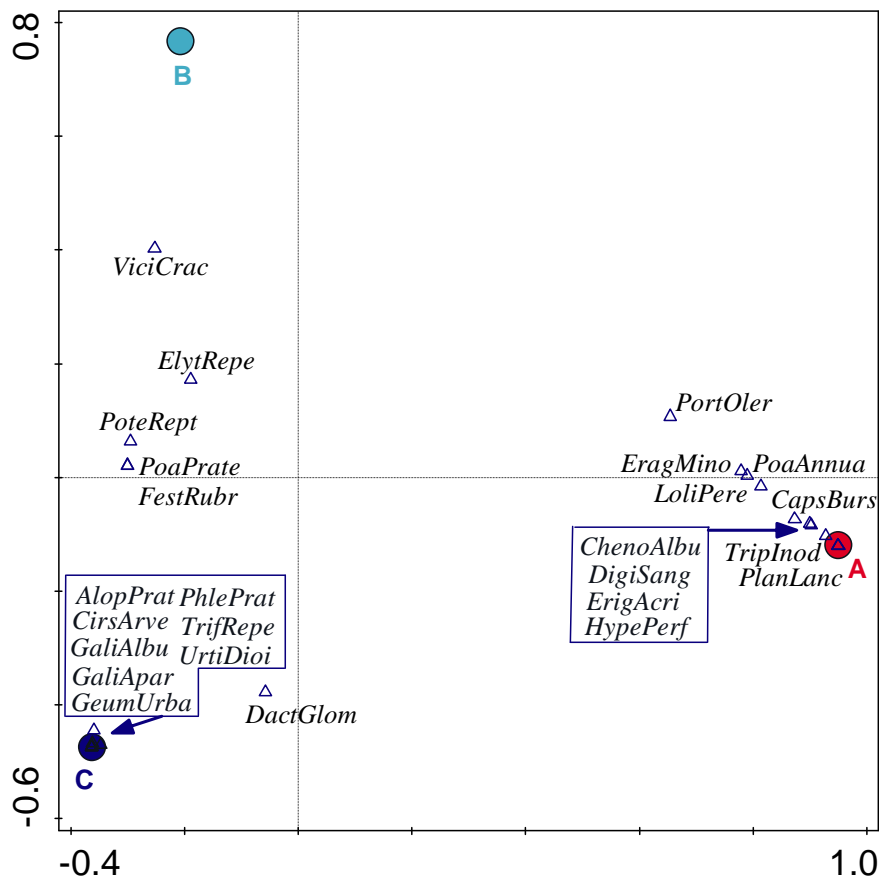


Fig. 13. Constrained unimodal ordination diagram (CCA) representing relationships between 25 best fitted plant species to the pipeline zone (A) or the outside zones (B, C) at the third site. Abbreviations are explained in Supplementary Material 3.

3.3 Soil temperature measurement

Soil temperature strongly decreased with the distance from the pipeline (Fig. 14, 15) suggesting great heating dissipation from the pipeline. A two-year average is more than 13 °C higher above the pipeline than 16 m outside the pipeline (Table 1).

Table 1. Mean soil temperatures (°C) measured in three transects at the study sites for year 1 (August 2010-July 2011) and year 2 (August 2011-July 2012) and comparison with air temperatures. **A** represents the pipeline zone, **A-B** the transition zone, **B** the zone 0.5 m outside the pipeline and **C** the zone 16 m outside the pipeline.

zone	A			A-B			B			C			air
	1	2	3	1	2	3	1	2	3	1	2	3	
year 1	22.4	21.9	24.6	21.6	20.1	23.4	17.4	16.4	19.8	10.8	10.8	8.7	8.7
year 2	24.3	23.3	24.5	23.0	21.8	22.8	18.6	17.5	20.3	10.8	12.0	9.4	9.4
two year average	23.5			22.1			18.3			10.3			9.1

Mean air temperatures were found to be very similar to mean temperatures from zone C providing an evidence that these plots are not influenced by heating dissipation off the pipeline. However, zone B was found to be strongly influenced (Fig. 14, 15). Heat from the pipeline thus likely penetrates more than 0.5 meters from the transition zone making a temperature gradient, but no temperature data were sampled for this zone.

Soil temperature maximum was recorded at the third site on 29 June 2011 at 14:30 and reached 53.6 °C (Table 2). Maximum temperatures measured within other sites were much lower, about 40 °C (Table 2). August 2011 was the hottest month at the first and the third site, while July 2012 was the hottest month at the second site.

Table 2. Maximum and minimum soil temperatures (°C) measured at the study sites from July 2010 to July 2012. **A** represents the pipeline zone, **A-B** the transition zone, **B** the zone 0.5 m outside the pipeline and **C** the zone 16 m outside the pipeline.

zone	A			A-B			B			C		
	1	2	3	1	2	3	1	2	3	1	2	3
temperature maximum	40.4	39.7	53.6	37.4	38.6	43.7	30.4	30.6	34.0	29.8	31.2	25.3
temperature minimum	1.7	4.1	3	5.9	4.4	4.7	2.2	0.7	4.2	-5.3	-7.0	-6.4

The second site seems to be colder than other sites (Fig. 14, 15). The steepest temperature gradient was recorded between zones A and C at the third site (Fig. 14, 15). Although the temperature detected in zones C is much lower than in zones A (Table 1, 2), daily courses of temperature follow similar trends regardless the place (Fig. 16, 17).

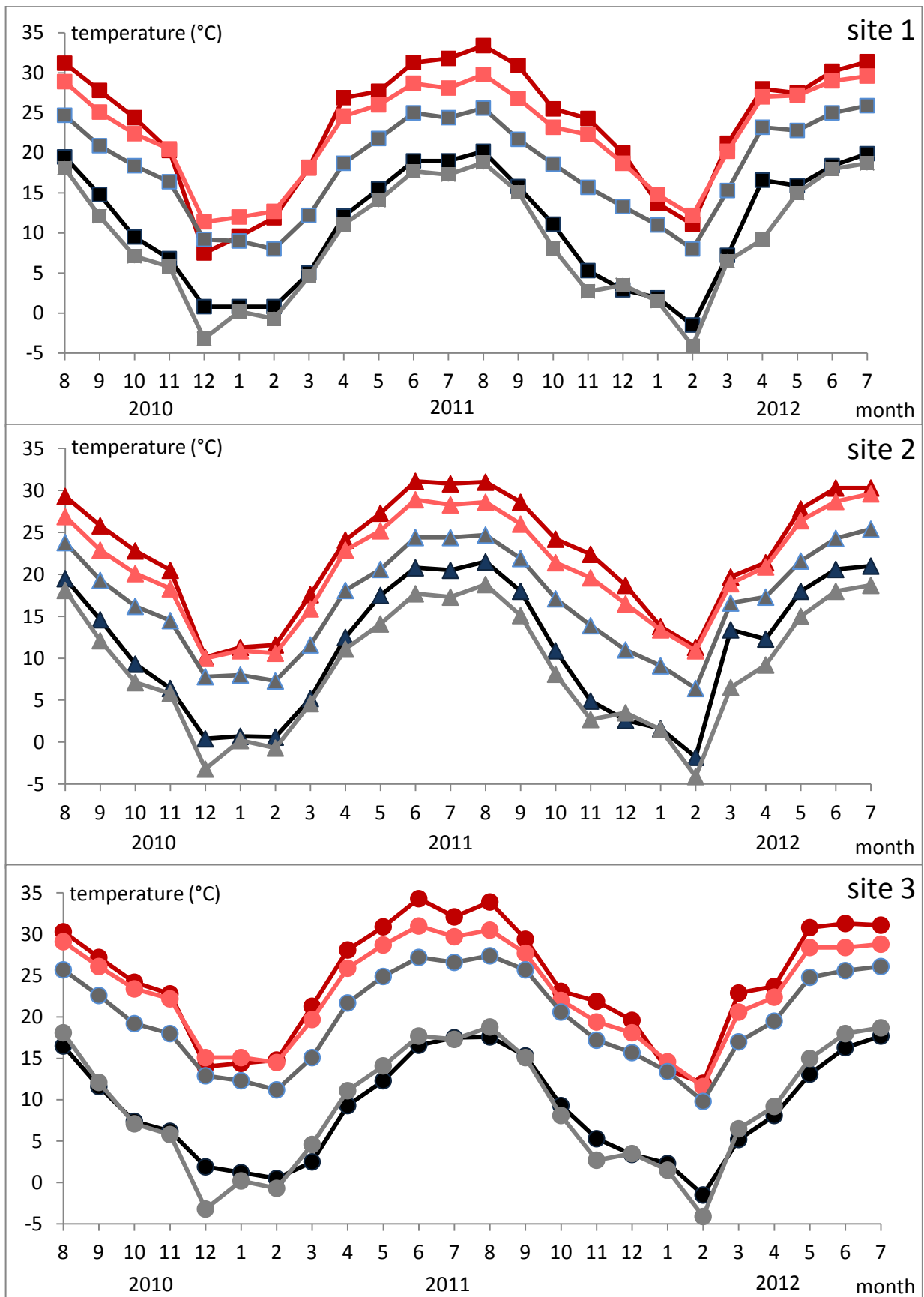


Fig. 14. Dynamics of soil and air temperature (°C) at the study sites during two years. Monthly averages are presented. Curves in red indicate the middle of the pipeline zone (zone A), curves in pink indicate the transition zone (zone A-B, the margin of the pipeline zone), curves in blue the zone 0.5 m from the pipeline (zone B), curves in dark blue the zone 15 m from the previous (zone C), and curves in gray air temperature. Air temperature data were provided by CHMI (Czech Hydrometeorological Institute) in České Budějovice.

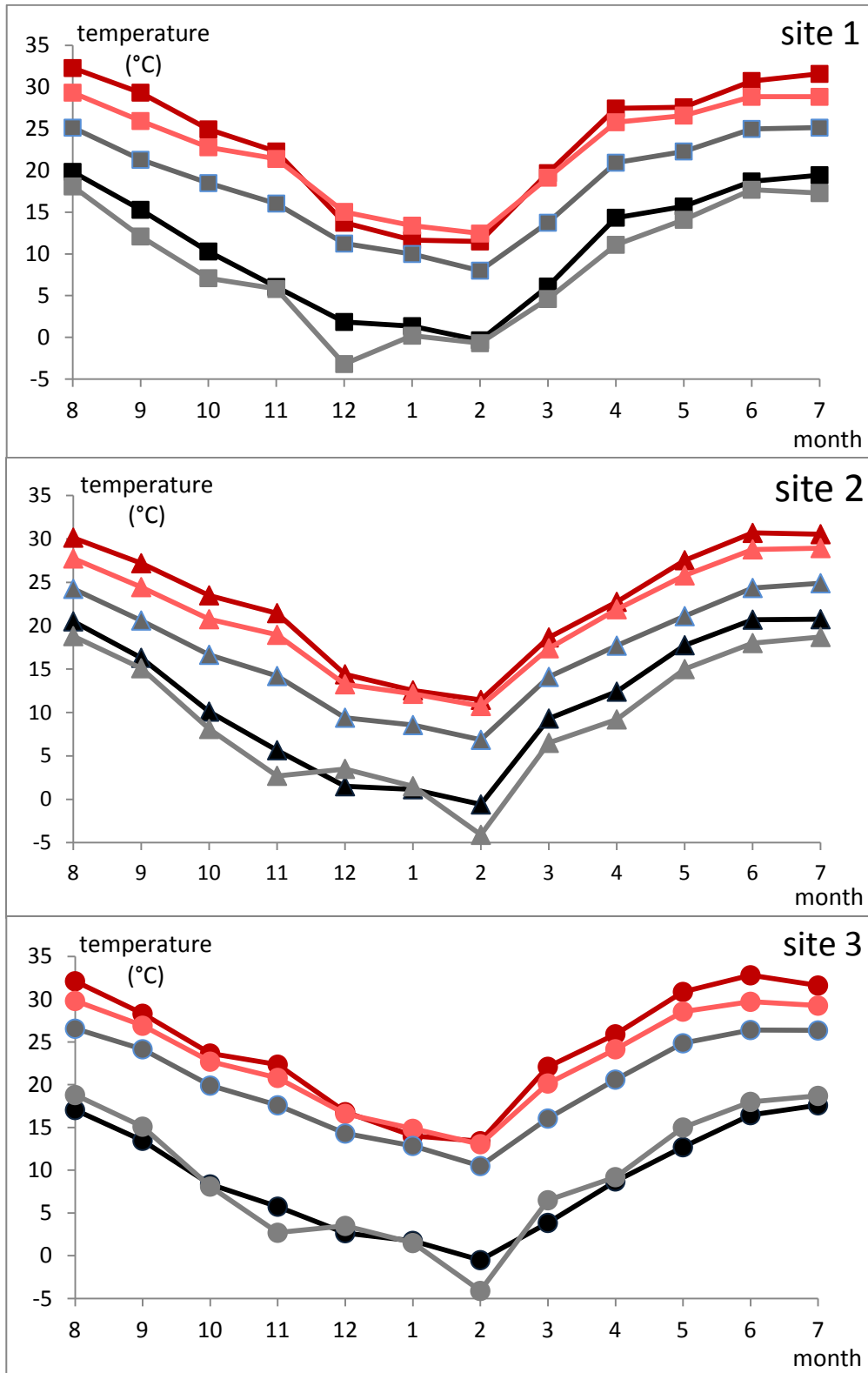


Fig. 15. Averaged monthly temperatures ($^{\circ}\text{C}$) calculated from two-year data measured at the study sites. Curves in red represent the middle of the pipeline zone (zone A), curves in pink the transition zone (zone A-B, the margin of the pipeline zone), curves in blue the zone 0.5 m from the pipeline (zone B), curves in dark blue the zone 15 m from the previous (zone C), and gray represent air temperature.

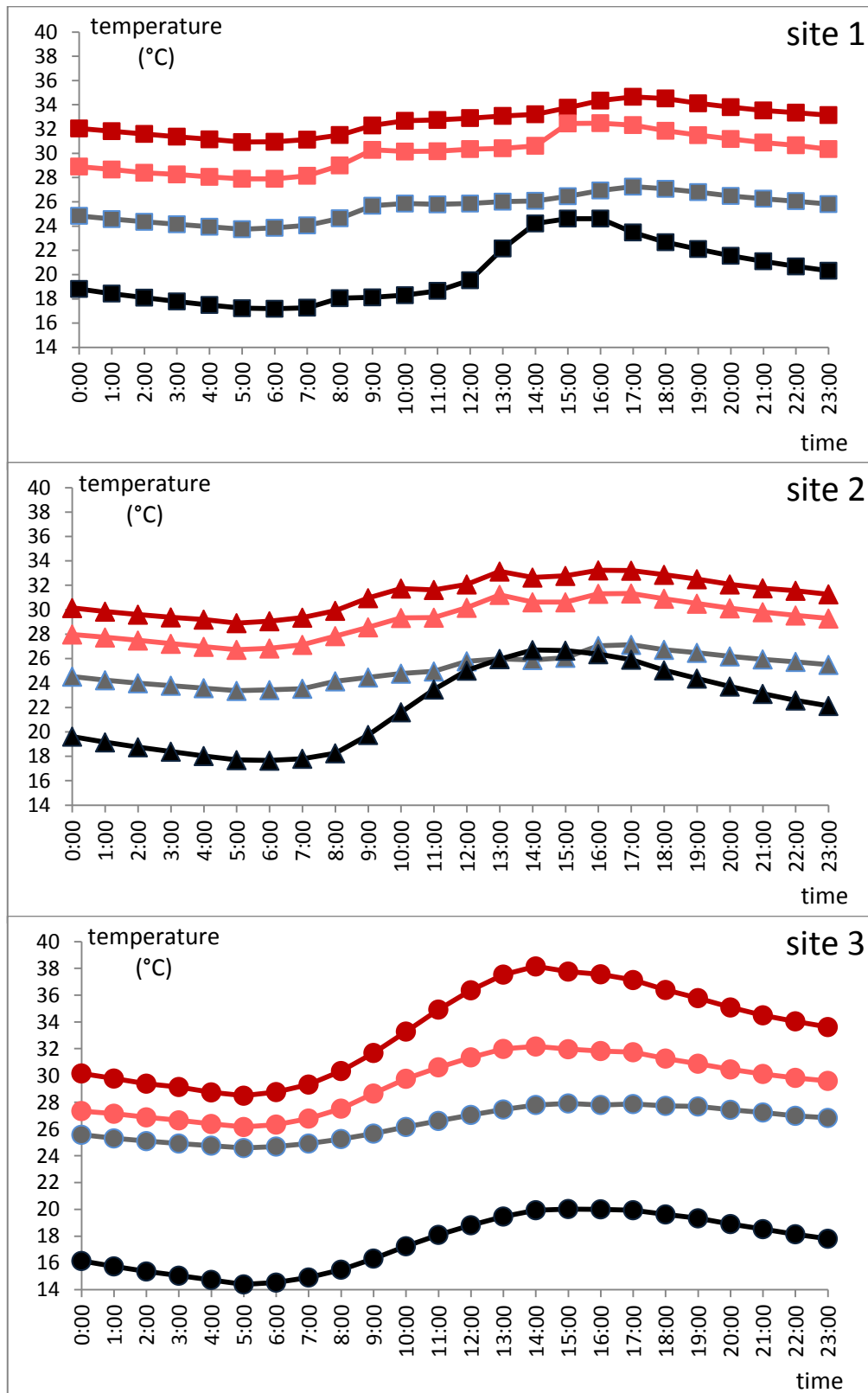


Fig. 16. Daily course of soil temperature (°C) at the study sites on sunny summer day (3 August 2011). Curves in red correspond to the middle of the pipeline zone (zone A), curves in pink to the transition zone (zone A-B, the margin of the pipeline zone), curves in blue to the zone 0.5 m from the pipeline (zone B) and curves in dark blue to the zone 15 m from the previous (zone C).

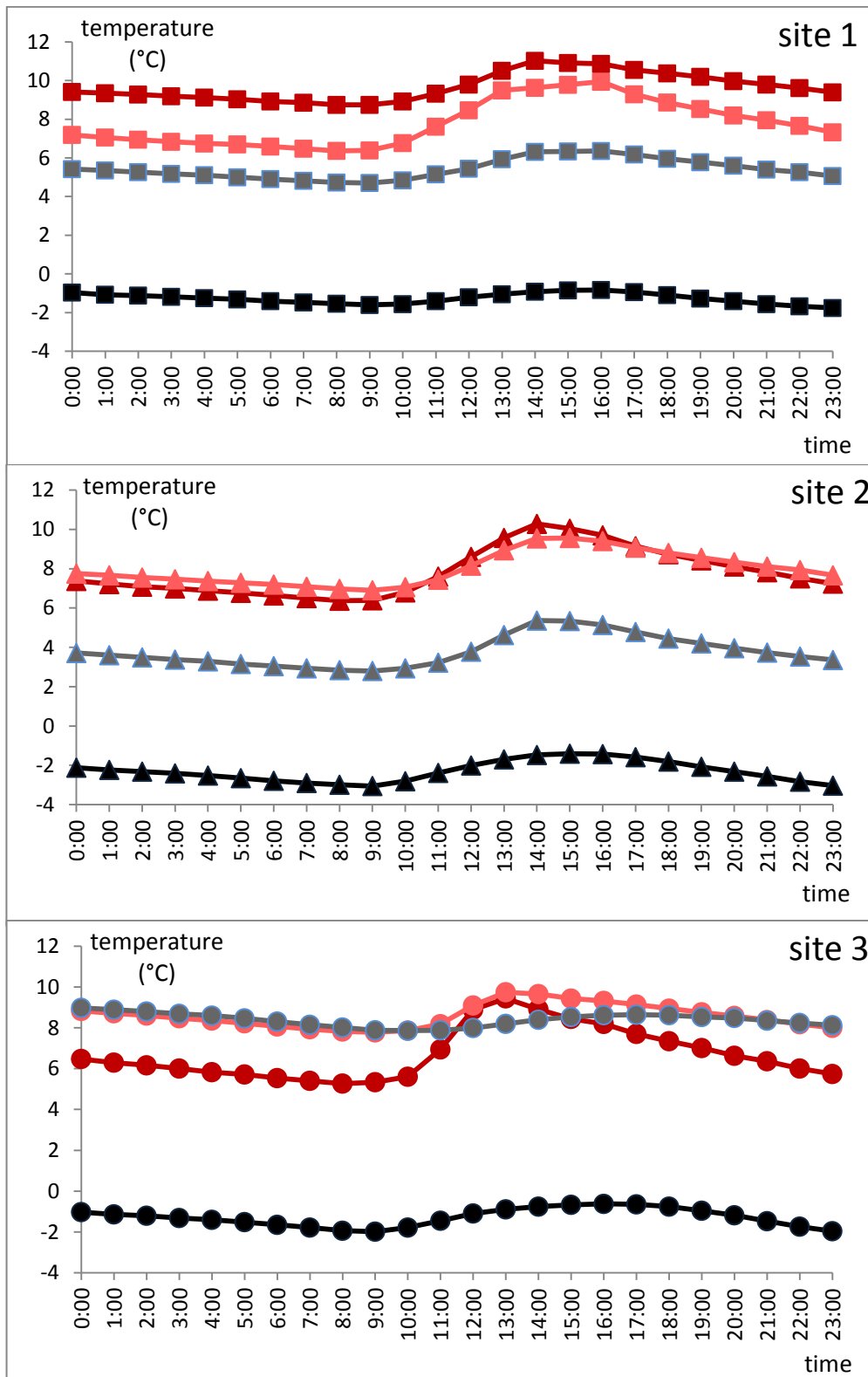


Fig. 17. Daily course of soil temperature (°C) at the study sites on sunny winter day (1 February 2012). Curves in red correspond to the middle of the pipeline zone (zone A), curves in pink to the transition zone (zone A-B, the margin of the pipeline zone), curves in blue to the zone 0.5 m from the pipeline (zone B) and curves in dark blue to the zone 15 m from the previous (zone C).

3.4 Soil moisture measurement

Soil moisture gradually increased with the distance from the pipeline (Fig. 18) indicating strong water vapor above the pipeline. Average volumetric water content measured from 1 December 2012 for a year was about 15% lower in the zone A compared to the zone B. Data from zones A-B and C are available only from December 2011 to February 2012, because dataloggers were broken.

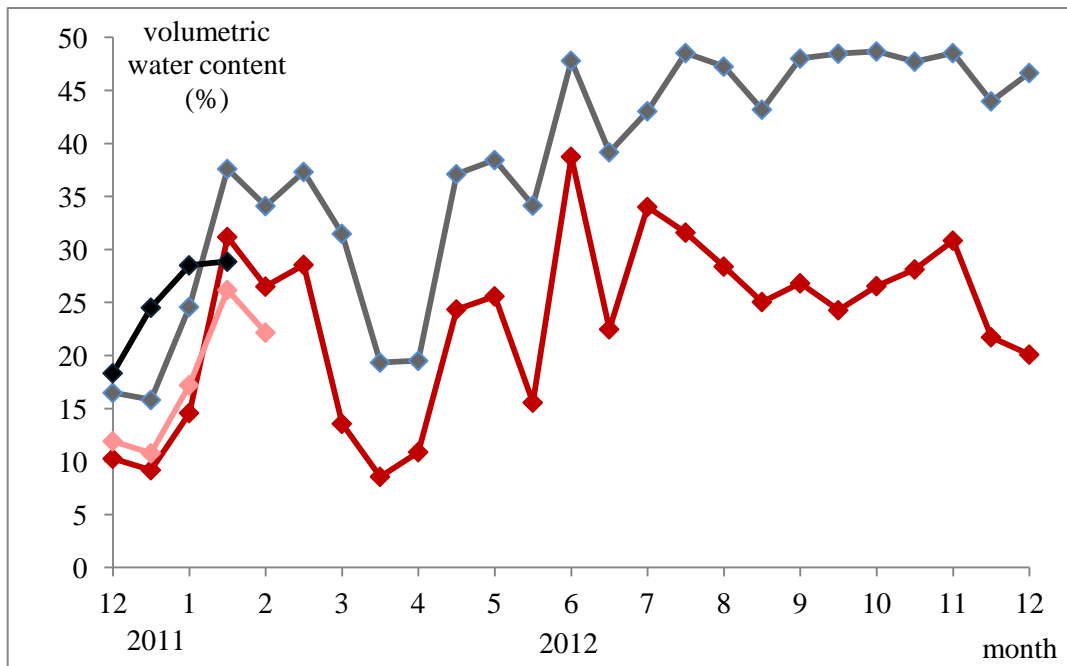


Fig. 18. Course of soil moisture expressed as volumetric water content (%) at the second study site during one year. Two-week averages are presented. Curves in red indicate the middle of the pipeline zone (zone A), curves in pink indicate the transition zone (zone A-B, the margin of the pipeline zone), curves in blue the zone 0.5 m from the pipeline (zone B), curves in dark blue the zone 15 m from the previous (zone C), and curves in gray air temperature.

3.4 Sowing experiments

3.4.1 Preliminary examination of germination rate

Total germination rate of studied species tested under fixed conditions after a month was 88% for *G. ciliata*, 62% for *S. inaequidens*, 48% for *S. jacobaea*, 35% for *S. viscosus*, and 0% for *T. procumbens*. Most seeds germinated within first two weeks (Table 3).

Table 3. Numbers of germinated seeds recorded every 1-6 days for a month. First column indicates number of days from sowing (day 0) and numbers in brackets correspond to the number of sown seeds.

species	<i>Galinsoga</i>	<i>Senecio</i>	<i>Senecio</i>	<i>Senecio</i>	<i>Tridax</i>
day	<i>ciliata</i> (50)	<i>inaequidens</i> (100)	<i>jacobaea</i> (100)	<i>viscosus</i> (100)	<i>procumbens</i> (50)
7	0	0	3	0	0
9	12	1	23	5	0
10	17	15	28	5	0
11	27	35	32	6	0
13	40	50	41	18	0
14	40	52	43	23	0
18	43	65	48	31	0
19	44	65	48	32	0
25	44	55	48	35	0
27	44	62	47	31	0

3.4.2 Laboratory germination experiment

Exposing seeds to the temperature gradient revealed optimal germination temperatures of studied species (Fig. 19). For *S. jacobaea* and *S. inaequidens* optimal germination temperature was at approximately 18 °C, whereas optimal germination temperatures for remaining species were higher. *G. ciliata* showed highest proportion of germination at 22-28 °C and *S. viscosus* and *T. probumbens* germinated predominantly at about 30 °C (Fig. 19). Proportion of germinated seeds significantly differed between species and across temperature gradient (Table 4).

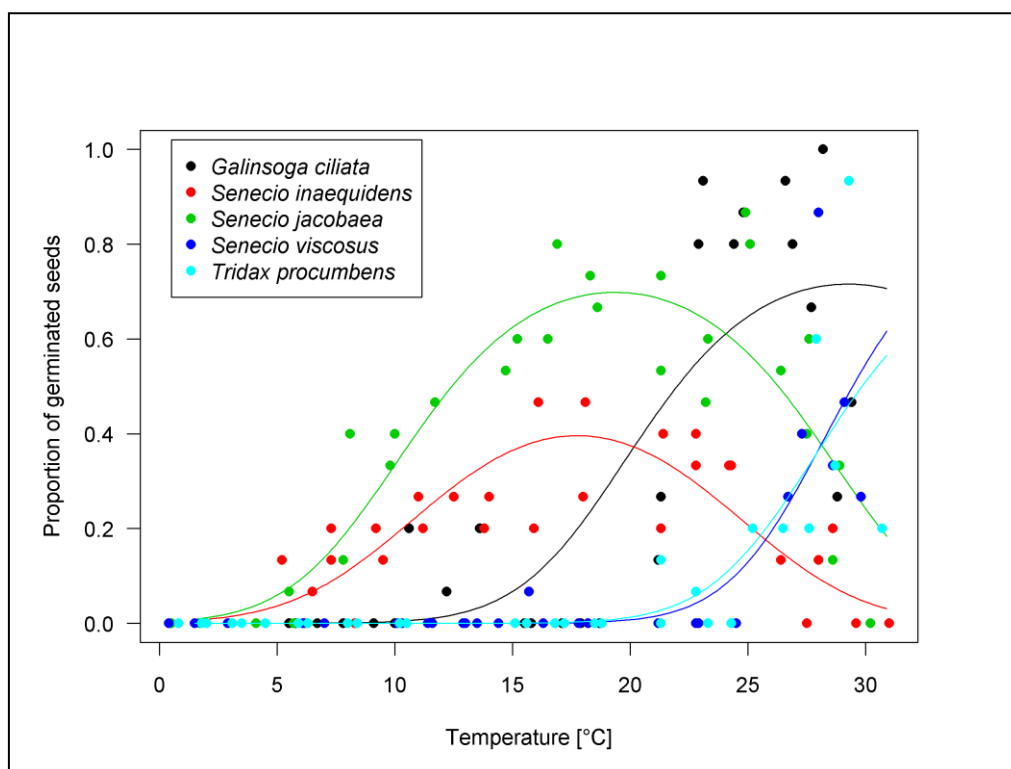


Fig. 19. Proportion of germinated seeds of studied species under the temperature gradient after one month. Only *S. jacobaea*, *S. inaequidens*, and *G. ciliata* are accurately fitted by the model.

Table 4. Summary of the quasibinomial generalized linear model (GLM) testing the effect of species, temperature and interaction of species and temperature on proportion of germinated seeds of studied species. Statistically significant test results ($P < 0.05$) are highlighted in bold.

Effect	df	Deviance	Residual deviance	F	P
Species	4,145	11.95	60.38	20.43	< 10^{-12}
Temperature (linear trend)	1,144	20.50	39.88	140.26	< 10^{-15}
Temperature ² (2 nd -degree polynomial trend)	1,143	2.17	37.71	14.83	< 0.001
Species × temperature	4,139	20.16	17.55	34.48	< 10^{-15}
Species × temperature ² (2 nd -degree polynomial trend)	4,135	0.37	17.18	0.63	0.6434

Proportion of germinated seeds within a half time of the experiment and the final number of germinated seeds showed the germination rate of studied species (Fig. 20). The fastest germination was recorded for *S. jacobaea*, followed by *S. inaequidens*, *T. procumbens*, *G. ciliata* and *S. viscosus* (Fig. 20). Decreasing curves imply an acceleration of germination time by higher temperatures for all the species.

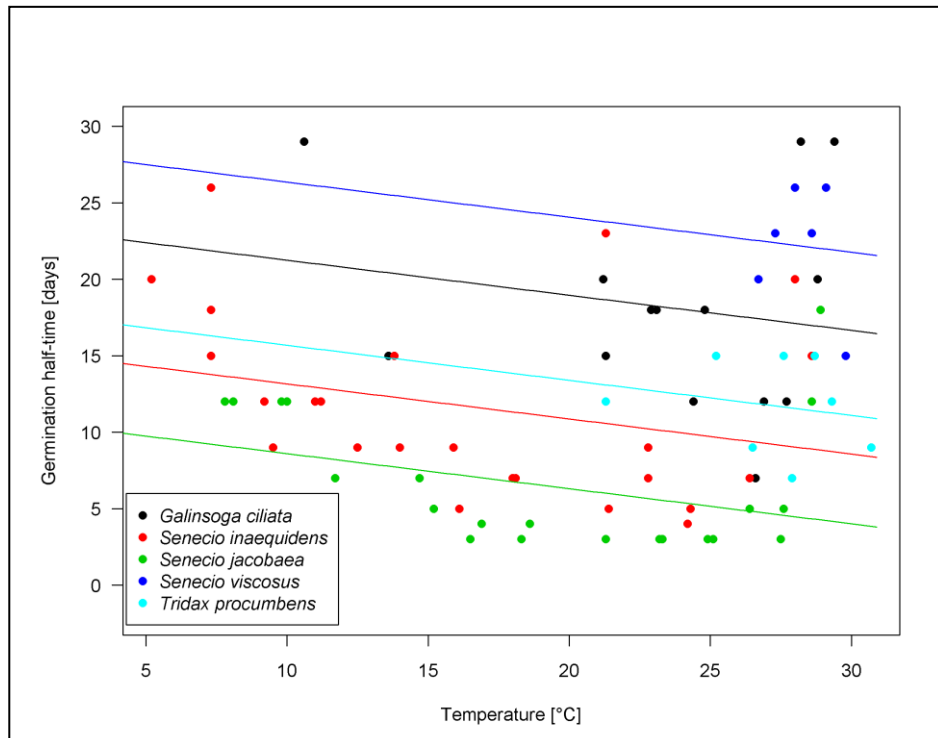


Fig. 20. Germination rate of studied species under the temperature gradient. Germination half-time relates to the number of days when more than half of total germinated seeds reached germination. Only *S. jacobaea*, *S. inaequidens*, and *G. ciliata* are accurately fitted by the model.

3.4.3 Field sowing experiment

Course of germination observed during the first 57 days after sowing was not different between zones A and C for any studied species except *T. procumbens* (Fig. 21-25, Table 5). *T. procumbens* showed a higher proportion of germinated seeds in the zone A in every observation time (Fig. 22). However, overall proportion of germinated seeds of *T. procumbens*, *S. viscosus* and *S. jacobaea* was very small regardless a zone (Fig. 22, 24, 25). *S. viscosus* was found to germinate preferentially in the zone C (Fig. 25).

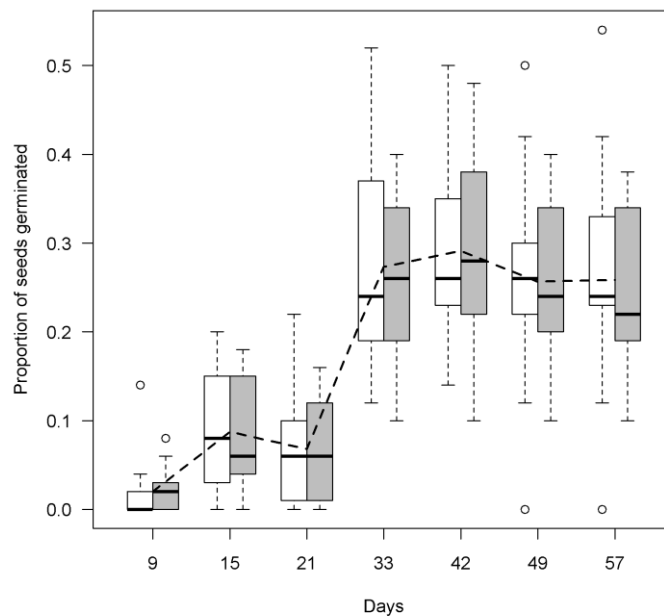


Fig. 21. Course of germination of *Galinsoga ciliata* above the pipeline (zone A, gray boxes) and outside the pipeline (zone C, white boxes) during 57 days after sowing. Boxes indicate 25% and 75% quantiles and whiskers indicate nonoutlier range of values. Empty circles represent outliers. Proportion of germinated seeds within observed days was not significantly different between zones A and C ($P = 0.6134$, Table 5).

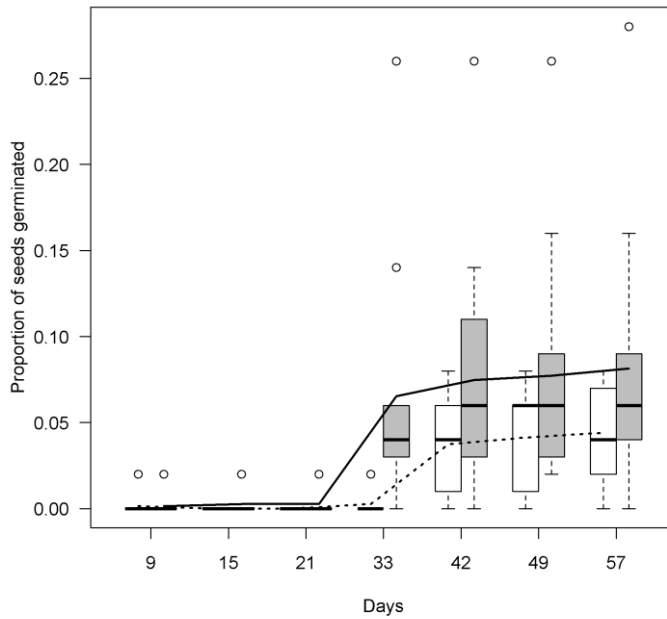


Fig. 22. Course of germination of *Tridax procumbens* above the pipeline (zone A, gray boxes, solid line) and outside the pipeline (zone C, white boxes, dotted line) during 57 days after sowing. Boxes indicate 25% and 75% quantiles and whiskers indicate nonoutlier range of values. Empty circles represent outliers. Numbers of germinated seeds significantly differed between zones A and C ($P < 10^{-8}$, Table 5).

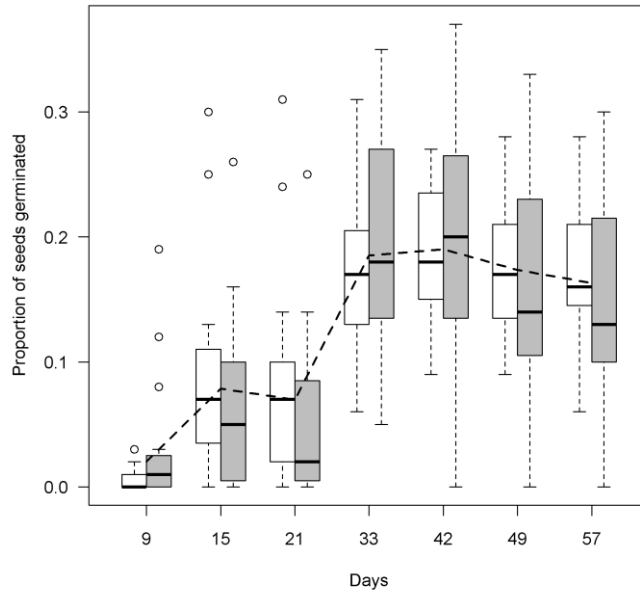


Fig. 23. Course of germination of *Senecio inaequidens* above the pipeline (zone A, gray boxes) and outside the pipeline (zone C, white boxes) during 57 days after sowing. Boxes indicate 25% and 75% quantiles and whiskers indicate nonoutlier range of values. Empty circles represent outliers. Numbers of germinated seeds were not significantly different between zones A and C ($P = 0.8756$, Table 5).

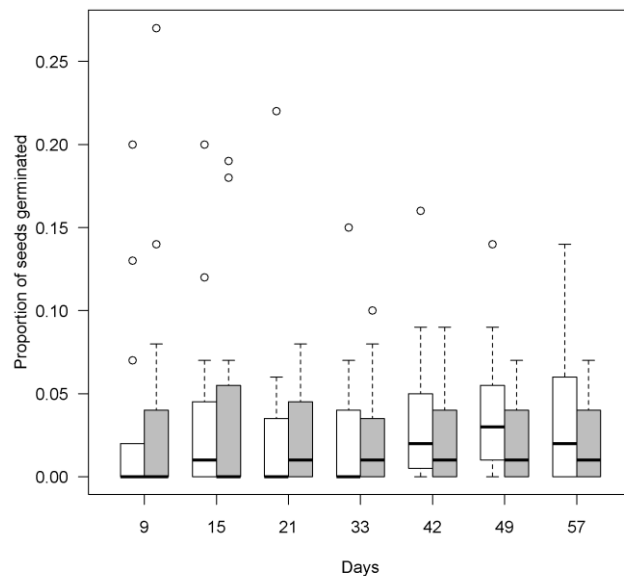


Fig. 24. Course of germination of *Senecio jacobaea* above the pipeline (zone A, gray boxes) and outside the pipeline (zone C, white boxes) during 57 days after sowing. Boxes indicate 25% and 75% quantiles and whiskers indicate nonoutlier range of values. Empty circles represent outliers. Numbers of germinated seeds were not significantly different between zones A and C ($P = 0.4565$, Table 5).

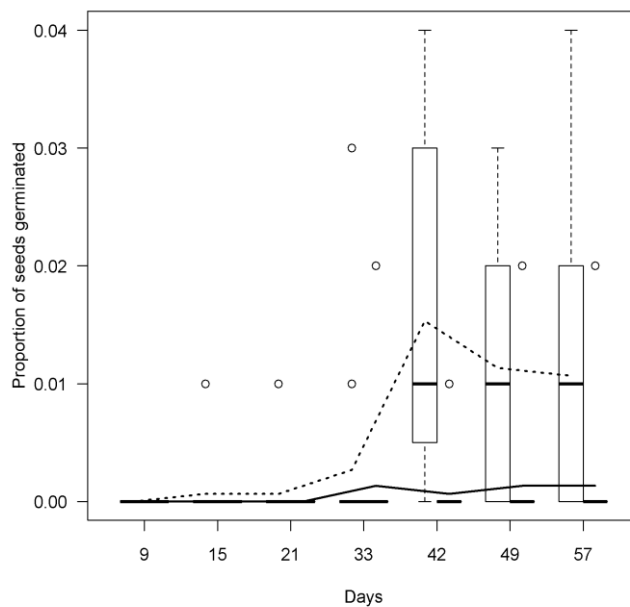


Fig. 25. Course of germination of *Senecio viscosus* above the pipeline (zone A, solid line) and outside the pipeline (zone C, white boxes, dotted line) during 57 days after sowing. Almost no seeds germinated above the pipeline. Boxes indicate 25% and 75% quantiles and whiskers indicate nonoutlier range of values. Empty circles represent outliers. Numbers of germinated seeds were not significantly different between zones A and C ($P = 0.8756$, Table 5).

Table 5. Summary of the general linear model (GLM) testing the effect of day, pipeline, and interaction of day and pipeline on course germination of studied species. GC indicates *G. ciliata*, TP *Tridax procumbens*, SI *Senecio inaequidens*, SJ *S. jacobaea*, and SV *S. viscosus*. Statistically significant test results ($P < 0.05$) are highlighted in bold.

Species	Effect	df	Deviance	Residual deviance	F	P
GC	day	6, 203	19.13	12.67	53.43	<10⁻¹⁵
	pipeline	1, 202	0.02	12.65	0.26	0.6134
	day × pipeline	6, 196	0.03	12.63	0.08	0.9982
TP	day	6, 203	6.59	7.02	35.77	<10⁻¹⁵
	pipeline	1, 202	1.21	5.81	39.26	<10⁻⁸
	day × pipeline	6, 196	0.57	5.24	3.09	0.0064
SI	day	6, 203	8.96	12.12	25.2	<10⁻¹⁵
	pipeline	1, 202	0	12.12	0.02	0.8756
	day × pipeline	6, 196	0.49	11.63	1.39	0.2223
SJ	day	6, 203	0.11	11.95	0.28	0.9481
	pipeline	1, 202	0.04	11.91	0.56	0.4565
	day × pipeline	6, 196	0.17	11.75	0.4	0.8798
SV	day	6, 203	8.96	12.12	25.2	<10⁻¹⁵
	pipeline	1, 202	0	12.12	0.02	0.8756
	day × pipeline	6, 196	0.49	11.63	1.39	0.2223

First flowers of *G. ciliata* were recorded on 20 July. At the same time, I recorded first buds of *T. procumbens* which converted to flowers in a week. Buds were observed earlier in the zone A than in B, estimate difference is about 7 days. Remaining species except *S. jacobaea* flowered later, *S. inaequidens* flowered from September to December, *S. viscosus* in early September. Unfortunately, phenology of flowered *Senecio* species was not comparable between zone A and C, because both zones were not cut at the same time from the end of summer.

Although *Senecio* species survived longer than the remaining species, all species except *S. viscosus* (grew only in zone C) survived longer in the zone A. *G. ciliata* and *T. procumbens* were observed about 30 days longer in the zone A than in C. *S. jacobaea* is still (12 December) surviving in the zone A and *S. inaequidens* is surviving in both zones.

3.4.4 Seed viability of *Tridax procumbens*

Seed viability test is still in progress, first seedlings are starting to emerge from seeds collected in zones A and C.

4. Discussion

4.1 Vegetation above the pipeline

Vegetation above the pipeline is characterized predominantly by short-lived plant species. While common native species dominate above the pipeline from the end of autumn to spring (e.g. *Poa annua*, *Stellaria media* agg., and *Capsella bursa-pastoris*), non-native species occupy this zone in summer (e.g. *Digitaria sanguinalis*, *Portulaca oleracea*, and *Eragrostis minor*). Most of these non-native species use C₄ or CAM photosynthetic pathways to utilize carbon dioxide. These pathways enable them to reach greater maximum quantum yield under higher temperatures and efficiently use water (Sage & Kubien 2003). Consequently, they have a competitive advantage under drier and warmer environmental conditions (i.e. above the pipeline) over species using C₃ photosynthetic pathway (Sage & Kubien 2003). However, Pearcy et al. (1981) suggested that not only high water use efficiency, but rather its interactions with rooting system and drought tolerance may advantage water-stressed C₄ species. Similar pattern switching from C₃ and C₄ vegetation between seasons was observed in the Great Plains of North America (Monson *et al.* 1983; Tieszen *et al.* 1997) and in the Sonoran desert (Mulroy & Rundel 1977) where dry and warm summer occurs (Barbour & Billings 1988). Thus, the temperature and moisture regimes on the studied pipeline can be tentatively analogized with those in the mentioned habitats.

Additionally, most of non-native species dominated above the pipeline in summer are archeophytes (*Digitaria sanguinalis*, *Setaria glauca*, and *Eragrostis minor*) and some are neophytes (*Portulaca oleracea*, *Geranium pyrenaicum*) according to Catalogue of alien plants of the Czech Republic (Pyšek *et al.* 2012). Compared to above the pipeline, non-native species were much less represented outside the pipeline. It suggests that the zone above the pipeline represents a hot spot where non-native or even invasive species might grow and reproduce. Moreover, this hot spot is situated within a larger urban heat island which is known to harbour non-native species and to promote their invasions to other ecosystems (Oke 1982; Lonsdale 1999; Duguay *et al.* 2006; Pyšek *et al.* 2012).

Leaking heat from the pipeline significantly affects composition of vegetation, but also accelerates critical phenological events such as bud burst and flowering. Temperature is considered to be a key factor controlling important physiological processes, among others phenology (Saxe *et al.* 2001), and advance in phenological events is a well known

response to increasing temperature (Arft *et al.* 1999; Natali *et al.* 2012). Thus, phenological shifts recently observed for various species are commonly attributed to temperature changes (Menzel *et al.* 2006; Khanduri *et al.* 2008). However, evaluation of these phenological shifts above the pipeline should be considered as preliminary, as not many species are shared between the pipeline and surrounding zones. Temperature gradient in close distance to the pipeline seems as more suitable place for such an observation. However, more detailed temperature data than currently available would be needed to reliably evaluate phenological changes associated to this zone.

Taking into account unusually high soil temperatures accompanied by rapid loss of soil moisture during the whole year, the zone above the pipeline can be considered as an extreme habitat for most of plant species native to the Czech Republic. Plants have to cope with desiccation in summer when vegetation cover on some plots decreases to 0%. In winter, snow layer rapidly thaws above the pipeline and aboveground plant tissues would have to cope with freezing air temperatures. Most of species commonly growing above the pipeline avoid these winter conditions through annual life cycle. Only a few annuals and biennials prosper on the pipeline zone in winter.

Numerous studies have been recently dedicated to experimental manipulations of climate in order to find out how are/will be different world ecosystems affected by climate change (Rustad *et al.* 2001; Wu *et al.* 2011; Michelsen *et al.* 2012). Environmental factors such as temperature (Harte & Shaw 1995), precipitation (Le Roux *et al.* 2005), atmospheric CO₂ (Williams *et al.* 2007) and nitrogen deposition (Dukes *et al.* 2005) have been manipulated either individually (Ziska 2003; Kudo *et al.* 2010) or combined (Zavaleta *et al.* 2003; Henry *et al.* 2005).

The impact of elevated temperature on vegetation structure and various plant traits has been widely investigated by field manipulations (Harte & Shaw 1995; Boeck *et al.* 2007; Yang *et al.* 2011; Natali *et al.* 2012; Buizer *et al.* 2012). Despite of number of experiments carried out, none of the experiments can be used as a straight-forward comparison to this study because of differences in heating method, intensity of heating, period of exposure and ecosystem studied.

Warming treatment in published studies was usually produced by one of four following heating facilities: overhead infrared heaters (Hovenden *et al.* 2008; Luo *et al.* 2010), open-top chambers (OTCs) (Jägerbrand *et al.* 2009; Sierra-Almeida & Cavieres 2010), night-time roofs (Sowerby *et al.* 2005; Sardans *et al.* 2008) or heating cables

(Akinola *et al.* 1998; Hartley *et al.* 2007). Overhead heaters are suspended 1-2.5 m above the soil surface and heat both air and soil (Harte *et al.* 2006). OTCs also manipulate air and soil temperatures (Dabros *et al.* 2010). In contrast to the previous devices, heating cables are placed at soil surface (Grime *et al.* 2008) or more frequently buried few centimetres underground (Hartley *et al.* 2007) and directly change soil temperature (Shen & Harte 2000). Other heating facilities were used scarcely (Beierkuhnlein *et al.* 2011). Manipulating temperature by heating cables is the most similar method to this study using pipeline-induced soil heating. Heating cables were used for the first time by Rykbost *et al.* (1975). Cables were buried 92 cm underground and increased the soil surface temperature by 3 °C. Purpose of the study was not to simulate climate change, but to validate feasibility of conveying waste water from power plants (25-40 °C) in pipelines under fields to increase crop yields.

The intensity of heating makes further comparisons almost impossible. While temperature near the soil surface was maintained in the majority of studies at about 1-3 °C above ambient temperature (Grime *et al.* 2000; Harte *et al.* 2006; Williams *et al.* 2007), the pipeline increases temperature at soil surface layer by more than 10 °C.

To distinguish heat-induced changes, the period of exposure of focal community to warming is crucial. In most of published studies, localities were heated for less than 10 years (Suttle *et al.* 2007; Peñuelas *et al.* 2007; Rollinson & Kaye 2012) and to my best knowledge, there are only two published studies with longer heat treatment (15 and 13 years; Harte *et al.* 2006; Grime *et al.* 2008). Moreover, warming treatment was applied in some cases only for a part of year (Grime *et al.* 2000; Dukes *et al.* 2005) or day (Sowerby *et al.* 2005; Sardans *et al.* 2008). Vegetation above the pipeline has been continuously heated since 1980s, which notably extends time used for heat treatment.

Warming experiments focused on urban lawn communities are very rare. Bijoor *et al.* (2008) examined impact of elevated temperature and fertilizer application on composition and nitrogen cycling of turfgrass (*Schedonorus phoenix*) lawn in Irvine, California. The lawn was heated about 4 °C by ceramic infrared heaters elevated 1 m above the soil surface and warming lasted for almost 1.5 years. Substantial increase in biomass of C₄ weed in heated plots was found, which strongly agrees with my observations of C₄ species abundance above the pipeline. Furthermore, C₄ weed rapidly increasing biomass was crabgrass (*Digitaria* sp.), which also dominated experimental plots above the pipeline during summer season. White *et al.* (2000) similarly showed that extreme heating event may favour C₄ grasses. In their study, three New Zealand perennial grasslands were

treated by 8h-exposure to more than 50 °C by a special computer-regulated chamber. The exposure resulted in an increase of C₄ species abundance by 41 % in communities containing both C₃ and C₄ species. With absence of C₄ species, productivity of exposed C₃ community drastically decreased suggesting important role of C₄ species in maintaining stability of community under short-term extreme events. Removal of either C₃ or C₄ grass from the grassland ecosystem influenced many various attributes of that ecosystem (Wardle *et al.* 1999). Although other studies consistently proved promoting C₄ species under experimentally elevated temperatures (Wan 2005; Sherry *et al.* 2008), Sherry *et al.* (2008) pointed out that C₄ species are not always facilitated by increased temperature and drought compare to C₃ species (Williams *et al.* 2007).

4.2 Soil temperature and moisture

Great difference of soil temperature measured above and outside the pipeline suggests massive heat leakage from the pipeline. Not only soil temperature, but also soil moisture is strongly influenced by leaking heat. Therefore, it could be assumed that zone above the pipeline is permanently warmer and drier compared to surrounding. Nevertheless, winter temperatures were not always highest immediately above the pipeline (Fig. 14, 17). These particular temperature decreases might be caused by rapid thawing of snow layer in this zone followed by loss of its isolation properties. In addition, the pipeline is not deposited at all the sites in the same depth which may explain slightly lower temperatures measured at site 2. Detected steepest temperature gradient between the pipeline and most remote plots may be caused by differences in vegetation cover, soil properties or inaccurately delimited distance from the pipeline.

4.3 Germination of studied species

Overall proportion of germinated seeds in the laboratory and in the field was highest among all studied species in the case of *G. ciliata*. Most seeds (80-100%) germinated under temperature gradient at 22-28 °C, but similarly high proportion of seeds reached germination within preliminary germination trial at 21 °C. These results are in agreement with Jursík *et al.* (2003), who found out even wider range of optimum germination temperature (12-28 °C) with germination rate of 85%. Moreover, they demonstrated that germination significantly decreases at 30 °C, which is also supported by this study. On the other hand, germination rate of seeds of *G. ciliata* in a field experiment

was much lower (30%). This can be attributed to strong dependence of germination of the species on soil temperature and moisture (Jursík *et al.* 2010), but other environmental factors such as light or disturbance can be also responsible for decreased germination in field experiments (Sweet 1986; Bernardová 2006). On the other hand, dormancy cannot be taken into account, as seeds of *G. ciliata* are primary dormant at most for 100 days after ripening (Jursík *et al.* 2003) and used seeds already overcome this period.

Compared to *G. ciliata*, *T. procumbens* is more inhibited by suboptimal temperatures and thus it optimally germinates only at temperatures ranging from 25-35 °C (Gyuimarães *et al.* 2000; Chauhan & Johnson 2008). Maximum proportion of its seeds germinated in my experiments at about 30 °C strongly supporting the previous finding but it should be mentioned that no higher temperature than 30 °C was possible to arrange in my experiment. While seeds exposed to temperature lower than 20 °C failed to germinate in this study, seeds in the study made by Gyuimarães *et al.* (2000) achieved germination rate of 5.4% at 20 °C and 1.3% at 15 °C. Such a low percentage of germination at lower temperatures may explain why no of 50 seeds subjected to 21 °C in preliminary trial germinated. Under field conditions, germination considerably declined with only 5% of sown seeds emerged. Dormancy of *T. procumbens* can be hypothesized as a reason of lower field emergence, but it is not known if seeds are dormant beyond its native range. In contrast, it is known that the species is highly sensitive to light and germinates predominantly from the surface layer (Chauhan & Johnson 2008).

S. inaequidens showed an ability to germinate in wide range of temperature (5-30 °C) with highest germination rate at about 18 °C. Wide range of temperatures suitable for germination of the species was already reported in several studies (Sans *et al.* 2004; López-García & Maillet 2005). Rapidity of germination observed by López-García & Maillet (2005) is also consistent with results of this study. Overall field germination rate was found to be about 50% lower than the germination rate observed in laboratory experiment. In contrast to the previous species, *S. inaequidens* is known to be dormant (Ernst 1998). According to López-García & Maillet (2005), the species can pose different levels of dormancy which prevent germination and emergence. Similar trend was observed for other weedy species (Bouwmeester & Karssen 1993).

Germination of *S. jacobaea* reflected similar wide range of temperature and similar optimal temperature as *S. inaequidens*. Recognized temperature range fully agree with results of Van der Meijden & Van der Waalskooi (1979) and optimal temperature was 3 °C lower in their study than detected here. Little bit different results with highest and fastest

germination at 20/30 °C (day/night) were gained by Baker-Kratz & Maguire (1984). Cameron (1935) noticed rapid germination rate of the species at 15 °C. Although overall proportion of seeds germinated under temperature gradient was doubled compared to *S. inaequidens*, only 2% of sown seeds emerged in a field. It could be caused by a seed dormancy invoked by desiccation of soil surface layer, where seeds occurred (Sheldon 1974).

Although overall proportion of germinated seeds of *S. viscosus* was similar to *S. inaequidens*, it was achieved at much higher temperatures (27-30 °C). I assume that this result can be an artifact caused by delayed germination start of this species when compared to the rest of species. As germination velocity increased with increased temperature, only seeds subjected to higher temperature had enough time to germinate. Contrary to quite high overall germination rate under temperature gradient, almost no seeds germinated in a field experiment. Many irregular environmental factors such as temperature, light and moisture might have contributed to this decreased germination rate (Fenner & Thompson 2005). General absence of germination studies devoted to this species complicates to specify exact reason for the lack of germination and further data would be needed.

4.4 Comparison of germination and survival between zones

Among all studied species, only *T. procumbens* was found to germinate differently between zones. Successful germination together with an advance in phenology and longer survival of the species was significant above the pipeline. Since the length of the season is main factor limiting the number of produced seeds (Fenner & Thompson 2005), prolonged growing season of *T. procumbens* above the pipeline may be essential for establishment of the species. However, its establishment can be properly evaluated only after much longer time period (Turnbull *et al.* 2000; Clark *et al.* 2007).

No difference in germination of remaining species between zones might be related to the fact that they already occur in the Czech Republic (Pyšek *et al.* 2012). Therefore they are probably adapted to local climate and are able of establishment without any support (e.g. of elevated temperature). In contrast, *T. procumbens* is thermophilic species invading areas with tropical and subtropical climate, but recently not reported from Europe (DAISIE 2009).

5. Conclusions

A two-year investigation of vegetation above the pipeline proved that its composition is highly affected by heat leakage from the pipeline. Vegetation above the pipeline is characterized especially by annual, often non-native, species. Many of these species are C₄ grasses which deal with warm and dry conditions above the pipeline better than other species. Hypothesis considering zone above the pipeline as a heat island where non-native thermophilic, potentially invasive, plant species can recruit and establish was confirmed in a comparative study based on artificial sowing of closely-related native and non-native species.

6. References

- Akinola MO, Thompson K, Buckland SM (1998) Soil seed bank of upland calcareous grassland after 6 years of climate and management manipulations. *Journal of Applied Ecology*, **35**, 544–552.
- Andersen RN, Menges RM, Conn JS (1985) Variability in velvetleaf (*Abutilon theophrasti*) and reproduction beyond its current range in North America. *Weed Science*, **33**, 507–512.
- Andersson S (2001) The genetic basis of floral variation in *Senecio jacobaea* (Asteraceae). *The Journal of Heredity*, **92**, 409–414.
- Arft AM, Walker MD, Gurevitch J, *et al.* (1999) Responses of tundra plants to experimental warming: meta-analysis of the International tundra experiment. *Ecological Monographs*, **69**, 491–511.
- Bain JF (1991) The biology of Canadian wees. 96. *Senecio jacobaea* L. *Canadian Journal of Plant Sciences*, **71**, 127–140.
- Baker H (1965) Characteristics and modes of origin of weeds. In: *The genetics of colonizing species* (eds: Baker H, Stebbins G), pp 147–172. New York, Academic.
- Baker-Kratz AL, Maguire JD (1984) Germination and dry-matter accumulation in dimorphic achenes of tansy ragwort (*Senecio jacobaea*). *Weed Science*, **32**, 539–545.
- Barbour WD, Billings MG Eds. (1988) *North American terrestrial vegetation*. Cambridge, New York, Melbourne, Madrid, Cambridge University Press. pp 434.
- Beierkuhnlein C, Thiel D, Jentsch A, Willner E, Kreyling J (2011) Ecotypes of European grass species respond differently to warming and extreme drought. *Journal of Ecology*, **99**, 703–713.
- Bergquist G, Bremer B, Bremer K (1992) Chloroplast DNA restriction site variation and phylogenetic interrelationships of some genera of the Heliantheae sensu lato (Asteraceae). *Nordic Journal of Botany*, **12**, 149–154.
- Bernardová A (2006) Ecological characteristics of nonindigenous congeners varying in their invasive success: Invasive *Galinsoga parviflora* (Cav) and *Galinsoga ciliata* (Raf) vs. *Ageratum houstonianum* (Mill). Bachelor thesis. University of South Bohemia, České Budějovice. pp 34.
- Bijoor NS, Czimeczik CI, Pataki DE, Billings SA (2008) Effects of temperature and fertilization on nitrogen cycling and community composition of an urban lawn. *Global Change Biology*, **14**, 2119–2131.
- Böhmer HJ, Heger T, Trepl J (2001) *Fallstudien zu gebietsfremden Arten in Deutschland – Case studies on Aliens Species in Germany: Robinia pseudoacacia, Reynoutria japonica, Senecio inaequidens, Dreissena polymorpha, Ondatra zibethicus, Mustela vison*. Berlin, Texte des Umweltbundesamtes.
- Bossdorf O, Lipowsky A, Prati D (2008) Selection of preadapted populations allowed *Senecio inaequidens* to invade Central Europe. *Diversity and Distributions*, **14**, 676–685.
- Bouwmeester HJ, Karssen CM (1993) Annual changes in dormancy and germination in seeds of *Sisymbrium officinale* (L) Scop. *New Phytologist*, **124**, 179–191.
- Bradshaw WE, Holzapfel CM (2006) Evolutionary response to rapid climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **312**, 1477–1478.
- Broennimann O, Thuiller W, Hughes G, Midgley GF, Alkemade JMR, Guisan A (2006) Do geographic distribution, niche property and life form explain plants' vulnerability to global change? *Global Change Biology*, **12**, 1079–1093.

- Brunel S (2003) *Plantes envahissantes de la région méditerranéenne*. Agence Méditerranéenne de l'environnement Languedoc-Roussillon, Agence Régionale Pour l'Environnement Provence-Alpes-Côte d'Azur. Montpellier. pp 51.
- Bruun HH (2010) Post-dispersal seed predation of woody forest species limits recolonization of forest plantations on ex-arable land. *Preslia*, **82**, 345–356.
- Buizer B, Weijers S, Van Bodegom PM, *et al.* (2012) Range shifts and global warming: ecological responses of *Empetrum nigrum* L. to experimental warming at its northern (high Arctic) and southern (Atlantic) geographical range margin. *Environmental Research Letters*, **7**, 025501. doi:10.1088/1748-9326/7/2/025501.
- Bürger R, Lynch M (1995) Evolution and extinction in a changing environment: a quantitative-genetic analysis. *Evolution*, **49**, 151–163.
- Cai W, Lengaigne M, Borlace S, *et al.* (2012) More extreme swings of the South Pacific convergence zone due to greenhouse warming. *Nature*, **488**, 365–369.
- Cameron E (1935) A study on the natural control of ragwort (*Senecio jacobaea*). *Journal of Ecology*, **23**, 266–321.
- Caño L, Escarré J, Vrieling K, Sans FX (2009) Palatability to a generalist herbivore, defence and growth of invasive and native *Senecio* species: testing the evolution of increased competitive ability hypothesis. *Oecologia*, **159**, 95–106.
- Chauhan BS, Johnson DE (2008) Germination ecology of two troublesome Asteraceae species of rainfed rice: siam weed (*Chromolaena odorata*) and coat buttons (*Tridax procumbens*). *Weed Science*, **56**, 567–573.
- Chen IC, Hill JK, Ohlemüller R, Roy DB, Thomas CD (2011) Rapid range shifts of species associated with high levels of climate warming. *Science*, **333**, 1024–1026.
- Chmura D (2004) Penetration and naturalization of invasive alien plant species (neophytes) in woodlands of the Silesian upland (southern Poland). *Nature Conservation*, **60**, 3–11.
- Clark JS, Macklin E, Wood L (1998) Stages and spatial scales of recruitment limitation in southern Appalachian forests. *Ecological Monographs*, **68**, 213–235.
- Clark CJ, Poulsen JR, Levey DJ, Osenberg CW (2007) Are plant populations seed limited? A critique and meta-analysis of seed addition experiments. *The American Naturalist*, **170**, 128–142.
- Crawley MJ (1990) The population-dynamics of plants. *Philosophical transactions of the Royal Society B: Biological Sciences.*, **330**, 125–140.
- Crider KK (2011) Predator interference with the cinnabar moth (*Tyria jacobaeae*) for the biological control of tansy ragwort (*Senecio jacobaea*). *Invasive Plant Science and Management*, **4**, 332–340.
- Dabros A, Fyles JW, Strachan IB (2010) Effects of open-top chambers on physical properties of air and soil at post-disturbance sites in northwestern Quebec. *Plant and Soil*, **333**, 203–218.
- DAISIE (2009) *Handbook of alien species in Europe* (JA Drake, Eds.). Knoxville, Springer. pp 399.
- Dalling JW, Muller-Landau HC, Wright SJ, Hubbell SP (2002) Role of dispersal in the recruitment limitation of neotropical pioneer species. *Journal of Ecology*, **90**, 714–727.
- Daniëls FJA, De Molenaar JG, Chytrý M, Tichý L (2011) Vegetation change in Southeast Greenland? Tasiilaq revisited after 40 years. *Applied Vegetation Science*, **14**, 230–241.
- De Boeck HJ, Lemmens CMHM, Gielen B, Malchair S, Carnol M (2007) Biomass production in experimental grasslands of different species richness during three years of climate warming, *Biogeosciences*, **4**, 4605–4629.

- De Sassi C, Tylianakis JM (2012) Climate change disproportionately increases herbivore over plant or parasitoid biomass. *PloS One*, **7**, e40557. doi:10.1371/journal.pone.0040557.
- Dimande AFP, Botha CJ, Prozesky L, Bekker L, Rösemann GM, Labuschagne L, Retief E (2007) The toxicity of *Senecio inaequidens* DC. *Journal of the South African Veterinary Association*, **78**, 121–129.
- Donnelly A, Caffarra A, Kelleher C, *et al.* (2012) Surviving in a warmer world: environmental and genetic responses. *Climate Research*, **53**, 245–262.
- Dossena M, Yvon-Durocher G, Grey J, Montoya JM, Perkins DM, Trimmer M, Woodward G (2012) Warming alters community size structure and ecosystem functioning. *Proceedings of the Royal Society B: Biological Sciences*, **279**, 3011–3019.
- Duguay S, Eigenbrod F, Fahrig L (2006) Effects of surrounding urbanization on non-native flora in small forest patches. *Landscape Ecology*, **22**, 589–599.
- Dukes JS, Chiariello NR, Cleland EE, *et al.* (2005) Responses of grassland production to single and multiple global environmental changes. *PLoS Biology*, **3**, e319. doi:10.1371/journal.pbio.0030319.
- Dullinger S, Hu K (2011) Experimental evaluation of seed limitation in alpine snowbed plants. *PloS One*, **6**, e21537. doi:10.1371/journal.pone.0021537.
- Easterling DR (2000) Climate extremes: observations, modeling, and impacts. *Science*, **289**, 2068–2074.
- Ehrlén J, Eriksson O (2000) Dispersal limitation and patch occupancy in forest herbs. *Ecology*, **81**, 1667–1674.
- Ehrlén J, Münzbergova Z, Diekmann M, Eriksson O (2006) Long-term assessment of seed limitation in plants: results from an 11-year experiment. *Journal of Ecology*, **94**, 1224–1232.
- Emery NC, Stanton ML, Rice KJ (2009) Factors driving distribution limits in an annual plant community. *New Phytologist*, **181**, 734–747.
- EPPO (2006) EPPO data sheet on Invasive Plants. *Senecio inaequidens*. [www document] URL <http://www.eppo.int/> [accessed 15 November 2012].
- Eriksson O, Ehrlén J (1992) Seed and microsite limitation of recruitment in plant populations. *Oecologia*, **91**, 360–364.
- Ernst WHO (1998) Invasion, dispersal and ecology of the South African neophyte *Senecio inaequidens* in The Netherlands: from wool alien to railway and road alien. *Acta Botanica Neerlandica*, **47**, 131–151.
- Fenner M, Thompson K Eds. (2005) *The Ecology of Seeds*. Cambridge, Cambridge University Press. pp 250.
- Gardner JL, Heinsohn R, Joseph L (2009) Shifting latitudinal clines in avian body size correlate with global warming in Australian passerines. *Proceedings of the Royal Society B: Biological Sciences*, **276**, 3845–3852.
- Gaston KJ (2009) Geographic range limits: achieving synthesis. *Proceedings of the Royal Society B: Biological Sciences*, **276**, 1395–406.
- Ghalambor CK, McKay JK, Carroll SP, Reznick DN (2007) Adaptive versus non-adaptive phenotypic plasticity and the potential for contemporary adaptation in new environments. *Functional Ecology*, **21**, 394–407.
- Gienapp P, Teplitsky C, Alho JS, Mills JA, Merilä J (2008) Climate change and evolution: disentangling environmental and genetic responses. *Molecular Ecology*, **17**, 167–178.
- Grime JP, Brown VK, Thompson K, *et al.* (2000) The response of two contrasting limestone grasslands to simulated climate change. *Science*, **289**, 762–765.
- Grime JP, Fridley JD, Askew AP, Thompson K, Hodgson JG, Bennett CR (2008) Long-term resistance to simulated climate change in an infertile grassland. *Proceedings of*

- the National Academy of Sciences of the United States of America*, **105**, 10028–10032.
- Gyuiamarães SC, Souza IF, Pinho EVR V (2000) Efeito de temperaturas sobre a germinação de sementes de erva-de-touro (*Tridax procumbens*). *Planta Daninha*, **18**, 457–464.
- Hansen J, Sato M, Ruedy R (2012) Perception of climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **109**, e2415–2423. doi:10.1073/pnas.1205276109.
- Hansen J, Sato M, Ruedy R, Lo K, Lea DW, Medina-Elizade M (2006) Global temperature change. *Proceedings of the National Academy of Sciences of the United States of America*, **103**, 14288–14293.
- Harper JL, Wood WA (1957) Biological flora of the British Isles. *Senecio jacobaea* L. *Journal of Ecology*, **45**, 617–637.
- Harte J, Saleska S, Shih T (2006) Shifts in plant dominance control carbon-cycle responses to experimental warming and widespread drought. *Environmental Research Letters*, **1**, 014001. doi: 10.1088/1747-9326/1/1/014001.
- Harte J, Shaw R (1995) Shifting dominance within a montane vegetation community: results of a climate-warming experiment. *Science*, **267**, 876–880.
- Hartley IP, Heinemeyer A, Evans SP, Ineson P (2007) The effect of soil warming on bulk soil vs. rhizosphere respiration. *Global Change Biology*, **13**, 2654–2667.
- Heath MR, Neat FC, Pinnegar JK, Reid DG, Sims DW, Wright PJ (2012) Review of climate change impacts on marine fish and shellfish around the UK and Ireland. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **22**, 337–367.
- Heger T, Böhmer HJ (2006) NOBANIS – Invasive Alien Species Fact Sheet – *Senecio inaequidens*. *Online Database of the European Network on Invasive Alien Species – NOBANIS* [www document] URL <http://www.nobasis.org/> [accessed 10 October 2012].
- Hegi G (1987) *Illustrierte Flora von Mittel-europa: Pteridophyta, Spermatophyta. Bd. VI. Angiospermae: Dicotyledones 4.* (HJ Conert, U Hamann, W Schultze-Motel, and G Wagenitz, Eds.). Berlin, Hamburg, Verlag Paul Parey.
- Henry H a L, Cleland EE, Field CB, Vitousek PM (2005) Interactive effects of elevated CO₂, N deposition and climate change on plant litter quality in a California annual grassland. *Oecologia*, **142**, 465–73.
- Hilliard OM (1977) *Compositae in Natal*. Pietermaritzburg, South Africa, University of Natal Press. pp 658.
- Hoegh-Guldberg O, Hughes L, McIntyre S, Lindenmayer DB, Parmesan C, Possingham HP, Thomas CD (2008) Assisted colonization and rapid climate change. *Science*, **321**, 345–346.
- Hoerling M, Eischeid J, Perlwitz J, Quan X, Zhang T, Pegion P (2012) On the increased frequency of Mediterranean drought. *Journal of Climate*, **25**, 2146–2161.
- Hoffmann AA, Sgrò CM (2011) Climate change and evolutionary adaptation. *Nature*, **470**, 479–485.
- Holm L, Doll E, Holm J, Pancho J, Herberger J (1997) *World Weeds: Natural Histories and Distribution*. New York, John Wiley and Sons. pp 1129.
- Holmgren M, Scheffer M, Ezcurra E, Gutiérrez JR, Mohren GMJ (2001) El Niño effects on the dynamics of terrestrial ecosystems. *Trends in Ecology & Evolution*, **16**, 89–94.
- Holt RD (1990) The microevolutionary consequences of climate change. *Trends in Ecology & Evolution*, **5**, 311–315.
- Honnay O, Hermy M, Coppin P (1999) Impact of habitat quality on forest plant species colonization. *Forest Ecology and Management*, **115**, 157–170.

- Hovenden MJ, Wills KE, Chaplin RE, Vander Schoor JK, Williams AL, Osanai Y, Newton PCD (2008) Warming and elevated CO₂ affect the relationship between seed mass, germinability and seedling growth in *Austrodanthonia caespitosa*, a dominant Australian grass. *Global Change Biology*, **14**, 1633–1641.
- Hubbell SP (1999) Light-gap disturbances, recruitment limitation, and tree diversity in a neotropical forest. *Science*, **283**, 554–557.
- Huber M, Knutti R (2011) Anthropogenic and natural warming inferred from changes in Earth's energy balance. *Nature Geoscience*, **5**, 31–36.
- Hughes L (2000) Biological consequences of global warming: is the signal already. *Trends in Ecology & Evolution*, **15**, 56–61.
- IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (S Solomon, D Qin, M Manning, Z Chen, M Marquis, KB Averyt, M Tignor, and HL Miller, Eds.). Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.
- Ipou JI, Touré A, Adou LMD, Touré Y, Aké S, Coast I, August A (2011) Influence of some cover leguminous plants on the infestation degree of cotton plant major weeds. *African Journal of Agricultural Research*, **6**, 1097–1108.
- Jägerbrand AK, Alatalo JM, Chrimes D, Molau U (2009) Plant community responses to 5 years of simulated climate change in meadow and heath ecosystems at a subarctic-alpine site. *Oecologia*, **161**, 601–610.
- Juenger T, Bergelson J (2000) Factors limiting rosette recruitment in scarlet gilia, *Ipomopsis aggregata*: seed and disturbance limitation. *Oecologia*, **123**, 358–363.
- Jump AS, Penuelas J (2005) Running to stand still: adaptation and the response of plants to rapid climate change. *Ecology Letters*, **8**, 1010–1020.
- Jursík M, Holec J, Soukup J, Venclová V (2010) Seasonal emergence of selected summer annual weed species in dependence on soil temperature. **2010**, 444–450.
- Jursík M, Soukup J, Venclová V, Holec J (2003) Seed dormancy and germination of shaggy soldier (*Galinsoga ciliata* Blake.) and common lambsquarter (*Chenopodium album* L.). *Plant, Soil and Environment*, **2003**, 511–518.
- Kabuce N, Priede N (2010) NOBANIS – Invasive Alien Species Fact Sheet – *Galinsoga quadriradiata*. *Online Database of the European Network on Invasive Alien Species – NOBANIS NOBANIS* [www document] URL <http://www.nobasis.org/> [accessed 15 October 2012].
- Karl TR, Trenberth KE (2003) Modern global climate change. *Science*, **302**, 1719–1723.
- Karlén W (2005) Recent global warming: an artifact of a too-short temperature record? *Ambio*, **34**, 263–264.
- Khanduri VP, Sharma CM, Singh SP (2008) The effects of climate change on plant phenology. *The Environmentalist*, **28**, 143–147.
- Kosaka Y, Saikia B, Mingki T, Tag H, Riba T, Ando K (2010) Roadside distribution patterns of invasive alien plants along an altitudinal gradient in Arunachal Himalaya, India. *Mountain Research and Development*, **30**, 252–258.
- Kubát K Eds. (2002) *Klíč ke květeně České republiky*. Praha, Academia.
- Kudo G, Kimura M, Kasagi T, Kawai Y, Hirao AS (2010) Habitat-specific responses of alpine plants to climatic amelioration: comparison of fellfield to snowbed communities. *Arctic, Antarctic, and Alpine Research*, **42**, 438–448.
- Kuhlbrodt T, Gregory JM (2012) Ocean heat uptake and its consequences for the magnitude of sea level rise and climate change. *Geophysical Research Letters*, **39**, L18608. doi:10.1029/2012GL052952.

- Kumar B, Vijayakumar M, Govindarajan R, Pushpangadan P (2007) Ethnopharmacological approaches to wound healing-exploring medicinal plants of India. *Journal of Ethnopharmacology*, **114**, 103–113.
- Lachmuth S, Durka W, Schurr FM (2010) The making of a rapid plant invader: genetic diversity and differentiation in the native and invaded range of *Senecio inaequidens*. *Molecular Ecology*, **19**, 3952–3967.
- Lafuma L, Maurice S (2007) Increase in mate availability without loss of self-incompatibility in the invasive species *Senecio inaequidens* (Asteraceae). *Oikos*, **116**, 201–208.
- Lawler JJ, Tear TH, Pyke C, *et al.* (2010) Resource management in a changing and uncertain climate. *Frontiers in Ecology and the Environment*, **8**, 35–43.
- Legendre P, Anderson MJ (1999) Distance-based Redundancy analysis: testing multispecies responses in multifactorial ecological experiments. *Ecological Monographs*, **69**, 1–24.
- Lelieveld J, Hadjinicolaou P, Kostopoulou E, *et al.* (2012) Climate change and impacts in the Eastern Mediterranean and the Middle East. *Climatic Change*, **114**, 667–687.
- Lepš J, Šmilauer P (2003) *Multivariate analysis of ecological data using CANOCO*. New York, Cambridge University Press. pp 269.
- Le Roux PC, McGeoch MA, J NM, Chown SL (2005) Effects of a short-term climate change experiment on a sub-Antarctic keystone plant species. *Global Change Biology*, **11**, 1628–1639.
- Levin DA, Clay K (1984) Dynamics of synthetic *Phlox drummondii* populations at species margin. *American Journal of Botany*, **71**, 1040–1050.
- Lonsdale WM (1999) Global patterns of plant invasions and the concept of invasibility. *Ecology*, **80**, 1522–1536.
- López-García MC, Maillet J (2005) Biological characteristics of an invasive south African species. *Biological Invasions*, **7**, 181–194.
- Loss SR, Terwilliger L a., Peterson AC (2011) Assisted colonization: integrating conservation strategies in the face of climate change. *Biological Conservation*, **144**, 92–100.
- Luo C, Xu G, Chao Z, *et al.* (2010) Effect of warming and grazing on litter mass loss and temperature sensitivity of litter and dung mass loss on the Tibetan plateau. *Global Change Biology*, **16**, 1606–1617.
- Lurgi M, López BC, Montoya JM (2012) Novel communities from climate change. *Philosophical Transactions of the Royal Society B: Biological Sciences.*, **367**, 2913–2922.
- Mack RN (1996) Predicting the identity and fate of plant invaders: emergent and emerging approaches. *Biological Conservation*, **78**, 107–121.
- Mann EM, Bradley RS, Hughes MK (1999) Northern hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations. *Geophysical Research Letters*, **26**, 759–762.
- Maron JL, Simms EL (1997) Effect of seed predation on seed bank size and seedling recruitment of bush lupine (*Lupinus arboreus*). *Oecologia*, **111**, 76–83.
- Marsico TD, Hellmann JJ (2009) Dispersal limitation inferred from an experimental translocation of *Lomatium* (Apiaceae) species outside their geographic ranges. *Oikos*, **118**, 1783–1792.
- McEvoy PB (1984) Dormancy and dispersal in dimorphic achenes of tansy ragwort, *Senecio jacobaea* L. (Compositae). *Oecologia*, **61**, 160–168.
- McEvoy PB, Cox CS (1987) Wind dispersal distances in dimorphic achenes of ragwort, *Senecio jacobaea*. *Ecology*, **68**, 2006–2015.

- McEvoy PB, Cox CS, James RR, Rudd NT (1989) Ecological mechanisms underlying successful biological weed control: field experiments with ragwort *Senecio jacobaea*. In: *Proceedings of the VII International Symposium on Biological Control of Weeds* pp 55–66.
- McLachlan JS, Hellmann JJ, Schwartz MW (2007) A framework for debate of assisted migration in an era of climate change. *Conservation biology*, **21**, 297–302.
- Menzel A, Sparks TH, Estrella N, *et al.* (2006) European phenological response to climate change matches the warming pattern. *Global Change Biology*, **12**, 1969–1976.
- Merilä J (2012) Evolution in response to climate change: in pursuit of the missing evidence. *Bioessays*, **34**, 811–818.
- Meyssignac B, Cazenave A (2012) Sea level: a review of present-day and recent-past changes and variability. *Journal of Geodynamics*, **58**, 96–109.
- Michelsen A, Rinnan R, Jonasson S (2012) Two decades of experimental manipulations of heaths and forest understory in the subarctic. *Ambio*, **41**, 218–30.
- Monson RK, Littlejohn RO, Williams GJ (1983) Photosynthetic adaptation to temperature in four species from the Colorado shortgrass steppe: a physiological model for coexistence. *Oecologia*, **58**, 43–51.
- Monty A, Mahy G (2010) Evolution of dispersal traits along an invasion route in the wind-dispersed *Senecio inaequidens* (Asteraceae). *Oikos*, **119**, 1563–1570.
- Monty A, Maurice S, Mahy G (2010) Phenotypic traits variation among native diploid, native tetraploid and invasive tetraploid *Senecio inaequidens* DC. (Asteraceae). *Biotechnology, Agronomy, Society and Environment*, **14**, 627–632.
- Mulroy TW, Rundel PW (1977) Annual plants - adaptation to desert environments. *Bioscience*, **27**, 109–114.
- Natali SM, Schuur E a. G, Rubin RL (2012) Increased plant productivity in Alaskan tundra as a result of experimental warming of soil and permafrost. *Journal of Ecology*, **100**, 488–498.
- Oke TR (1982) The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*, **108**, 1–24.
- Orrock JL, Levey DJ, Danielson BJ, Damschen EI (2006) Seed predation, not seed dispersal, explains the landscape-level abundance of an early-successional plant. *Journal of Ecology*, **94**, 838–845.
- Parmesan C (2006) Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution, and Systematics*, **37**, 637–669.
- Parmesan C, Yohe G (2003) A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, **421**, 37–42.
- Parsons WT, Cuthbertson EG (2001) *Noxious Weeds of Australia*. Collingwood, Australia, CSIRO Publishing. pp 705.
- Pearcy RW, Tumosa N, Williams K (1981) Relationships between growth, photosynthesis and competitive interactions for a C₃ and a C₄ plant. *Oecologia*, **48**, 371–376.
- Pearson TRH, Burslem DFRP, Mullins CE, Dalling JW (2002) Germination ecology of neotropical pioneers: interacting effects of environmental conditions and seed size. *Ecology*, **83**, 2798–2807.
- Peñuelas J, Prieto P, Beier C, *et al.* (2007) Response of plant species richness and primary productivity in shrublands along a north–south gradient in Europe to seven years of experimental warming and drought: reductions in primary productivity in the heat and drought year of 2003. *Global Change Biology*, **13**, 2563–2581.
- Poole AL, Cairns D (1940) *Biological aspects of ragwort (Jacobaea vulgaris L.) control*. Wellington, Bulletin, Department of Scientific and Industrial Research, Government Printer.

- Prach K, Košnar J, Klimešová J, Hais M (2009) High Arctic vegetation after 70 years: a repeated analysis from Svalbard. *Polar Biology*, **33**, 635–639.
- Primack RB, Miao SL (1992) Dispersal can limit local plant distribution. *Conservation Biology*, **6**, 513–519.
- Primack RB, Miller-Rushing AJ (2009) The role of botanical gardens in climate change research. *New Phytologist*, **182**, 303–313.
- Prince SD, Carter RN (1985) The geographical distribution of prickly lettuce (*Lactuca serriola*): III . Its Performance in transplant sites beyond its distribution limit in Britain. *Journal of Ecology*, **73**, 49–64.
- Pyšek P, Chytrý M, Pergl J, Sádlo J, Wild J (2012) Plant invasions in the Czech Republic: current state, introduction dynamics, invasive species and invaded habitats. *Preslia*, **84**, 575–629.
- Pyšek P, Danihelka J, Sádlo J, *et al.* (2012) Catalogue of alien plants of the Czech Republic (2nd edition): checklist update , taxonomic diversity and invasion patterns. *Preslia*, **84**, 155–255.
- R Development Core Team (2012) R: a language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. [www document] URL <http://www.R-project.org/> [accessed 15 November 2012]
- Réale D, McAdam AG, Boutin S, Berteaux D (2003) Genetic and plastic responses of a northern mammal to climate change. *Proceedings of the Royal Society B: Biological Sciences*, **270**, 591–596.
- Rey PJ, Ramírez JM, Sánchez-Lafuente AM (2005) Seed- vs. microsite-limited recruitment in a myrmecochorous herb. *Plant Ecology*, **184**, 213–222.
- Rollinson CR, Kaye MW (2012) Experimental warming alters spring phenology of certain plant functional groups in an early successional forest community. *Global Change Biology*, **18**, 1108–1116.
- Root TL, MacMynowski DP, Mastrandrea MD, Schneider SH (2005) Human-modified temperatures induce species changes: Joint attribution. *Proceedings of the National Academy of Sciences of the United States of America*, **102**, 7465–7469.
- Root TL, Price JT, Hall KR, Schneider SH (2003) Fingerprints of global warming on wild animals and plants. *Nature*, **421**, 57–60.
- Root TL, Schneider SH (2006) Conservation and climate change: the challenges ahead. *Conservation Biology*, **20**, 706–708.
- Rustad L, Campbell J, Marion G, *et al.* (2001) A meta-analysis of the response of soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming. *Oecologia*, **126**, 543–562.
- Rykbost KA, Boersma L, Mack HJ, Schmisser WE (1975) Yield response to soil warming: vegetable crops. *Agronomy Journal*, **67**, 738–743.
- Sage RF, Kubien DS (2003) Quo vadis C(4)? An ecophysiological perspective on global change and the future of C(4) plants. *Photosynthesis research*, **77**, 209–225.
- Saino N, Ambrosini R, Rubolini D, *et al.* (2010) Climate warming, ecological mismatch at arrival and population decline in migratory birds. *Proceedings of the Royal Society B: Biological Sciences*, **278**, 835–842.
- Samy RP, Ignacimuthu S, Raja DP (1999) Preliminary screening of ethnomedicinal plants from India. *Journal of Ethnopharmacology*, **66**, 235–240.
- Sans FX, Garcia-Serrano H, Afán I (2004) Life-history traits of alien and native senecio species in the Mediterranean region. *Acta Oecologica*, **26**, 167–178.
- Sardans J, Peñuelas J, Estiarte M (2008) Warming and drought change trace element bioaccumulation patterns in a Mediterranean shrubland. *Chemosphere*, **70**, 874–885.

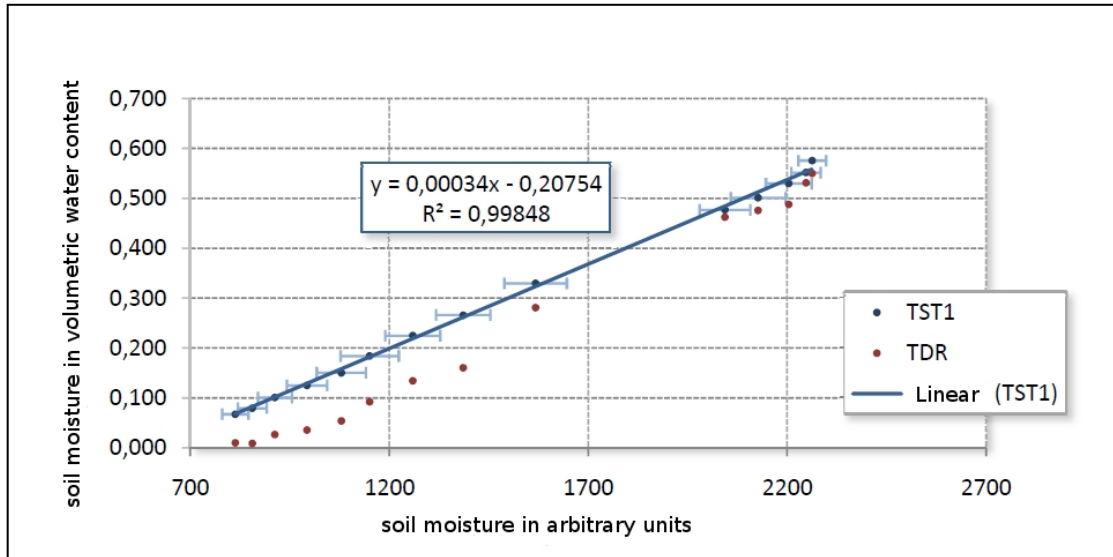
- Sardans J, Rivas-Ubach A, Peñuelas J (2012) The C:N:P stoichiometry of organisms and ecosystems in a changing world: A review and perspectives. *Perspectives in Plant Ecology, Evolution and Systematics*, **14**, 33–47.
- Savolainen O, Pyhäjärvi T (2007) Genomic diversity in forest trees. *Current Opinion in Plant Biology*, **10**, 162–167.
- Saxe H, Cannell MGR, Johnsen Ø, Ryan MG, Vourlitis G (2001) Tree and forest functioning in response to global warming. *New Phytologist*, **149**, 369–400.
- Schmitz G, Werner DJ (2001) The importance of the alien plant *Senecio inaequidens* DC. (Asteraceae) for phytophagous insects. *Zeitschrift für Ökologie und Naturschutz*, **9**, 153–160.
- Sharrow SH, Ueckert DN, Johnson AE (1988) Ecology and toxicology of *Senecio species* with special reference to *Senecio jacobaea* and *Senecio longilobus*. In: *The Ecology and Economic Impact of Poisonous Plants on Livestock Production* (eds: James LF, Ralphs MH, Nielsen DB), pp 181–196. Boulder, Colorado, Westview Press.
- Sheldon JC (1974) The behaviour of seeds in soil. 3. The influence of seed morphology and the behaviour of seedlings on the establishment of plants from surface-lying seeds. *Journal of Ecology*, **62**, 47–66.
- Shen KP, Harte J (2000) Ecosystem climate manipulations. In: *Methods in Ecosystem Science* (eds: Sala OE, Jackson RB, Mooney HA, Howarth RB), pp 353–370. New York, Springer-Verlag.
- Sheppard CS, Alexander JM, Billeter R (2012) The invasion of plant communities following extreme weather events under ambient and elevated temperature. *Plant Ecology*, **213**, 1289–1301.
- Sherry R a., Weng E, Arnone Iii J a., *et al.* (2008) Lagged effects of experimental warming and doubled precipitation on annual and seasonal aboveground biomass production in a tallgrass prairie. *Global Change Biology*, **14**, 2923–2936.
- Sierra-Almeida A, Cavieres L a (2010) Summer freezing resistance decreased in high-elevation plants exposed to experimental warming in the central Chilean Andes. *Oecologia*, **163**, 267–276.
- Sowerby A, Emmett B, Beier C, *et al.* (2005) Microbial community changes in heathland soil communities along a geographical gradient: interaction with climate change manipulations. *Soil Biology and Biochemistry*, **37**, 1805–1813.
- Sparks TH, Jeffree EP, Jeffree CE (2000) An examination of the relationship between flowering times and temperature at the national scale using long-term phenological records from the UK. *International Journal of Biometeorology*, **44**, 82–87.
- Suttle KB, Thomsen M a, Power ME (2007) Species interactions reverse grassland responses to changing climate. *Science*, **315**, 640–642.
- Sweet RD (1986) *Life History Studies as Related to Weed Control in the Northeast*. 9. *Galinsoga*. New York, Cornell University. pp 34.
- Ter Braak CJF, Šmilauer P (2012) Canoco 5, Windows release (5.00). [Software for canonical community ordination]. Microcomputer Power, Ithaca.
- Thomas CD, Cameron A, Green RE, *et al.* (2004) Extinction risk from climate change. *Nature*, **427**, 145–148.
- Tieszen LL, Reed BC, Bliss NB, Wylie BK, Dejong DD (1997) NDVI, C₃ and C₄ production, and distributions in Great Plains grassland land cover classes. *Ecological Applications*, **7**, 59–78.
- Tilman D (1997) Community invasibility, recruitment limitation, and grassland biodiversity. *Ecology*, **78**, 81–92.
- Turnbull LA, Crawley MJ, Rees M (2000) Are plant populations seed-limited? A review of seed sowing experiments. *Oikos*, **88**, 225–238.

- Turnbull LA, Manley L, Rees M (2005) Niches, rather than neutrality, structure a grassland pioneer guild. *Proceedings of the Royal Society B: Biological Sciences*, **272**, 1357–1364.
- Turnbull LA, Rees M, Crawley MJ (1999) Seed mass and the competition/colonization trade-off: a sowing experiment. *Journal of Ecology*, **87**, 899–912.
- USDA (2010) Natural Resources Conservation Service. Federal noxious weed list (1 May 2010) [www document] URL <http://www.nrcs.usda.gov/> [accessed 5 November 2012].
- Vanparrys V (2011) Comparative study of the reproductive ecology of two co-occurring related plant species: the invasive *Senecio inaequidens* and the native *Jacobaea vulgaris*. *Plant Ecology and Evolution*, **144**, 3–11.
- Van der Meijden E, Van der Waalskooi RE (1979) Population ecology of *Senecio jacobaea* in a sand dune system. 1. Reproductive strategy and the biennial habit. *Journal of Ecology*, **67**, 131–153.
- Van der Veken S, De Frenne P, Baeten L, Van Beek E, Verheyen K, Hermy M (2012) Experimental assessment of the survival and performance of forest herbs transplanted beyond their range limit. *Basic and Applied Ecology*, **13**, 10–19.
- Van der Veken S, Rogister J, Verheyen K, Hermy M, Nathan R (2007) Over the (range) edge: a 45-year transplant experiment with the perennial forest herb *Hyacinthoides non-scripta*. *Journal of Ecology*, **95**, 343–351.
- Vitasse Y, Bresson CC, Kremer A, Michalet R, Delzon S (2010) Quantifying phenological plasticity to temperature in two temperate tree species. *Functional Ecology*, **24**, 1211–1218.
- Vlček V (2010) Kalibrace vlhkostního čidla TST1 pro minerální a organické půdy. Bachelor thesis. České vysoké učení technické, Prague. pp 55.
- Walther G (2003) Plants in a warmer world. *Perspectives in Plant Ecology, Evolution and Systematics*, **6**, 169–185.
- Walther G, Post E, Convey P, *et al.* (2002) Ecological responses to recent climate change. *Nature*, **416**, 389–395.
- Wan S (2005) Direct and indirect effects of experimental warming on ecosystem carbon processes in a tallgrass prairie. *Global Biogeochemical Cycles*, **19**, GB2014. doi:10.1029/2004GB002315.
- Wardle DA (1987) The ecology of ragwort (*Senecio jacobaea* L.) - A review. *New Zealand Journal of Ecology*, **10**, 67–76.
- Wardle DA, Bonner KI, Barker GM, *et al.* (1999) Plant removals in perennial grassland: vegetation dynamics, decomposers, soil biodiversity, and ecosystem properties. *Ecological Modelling*, **69**, 535–568.
- Wardle DA, Nicholson KS, Rahman A (1995) Ecological effects of the invasive weed species *Senecio jacobaea* L. (ragwort) in a New Zealand pasture. *Agriculture, Ecosystems & Environment*, **56**, 19–28.
- Warwick SI, Briggs D, Street D (1978) Variation in four populations of *Senecio viscosus* L. *New Phytologist*, **81**, 391–400.
- Watson LE, Jansen RK, Estes JR (1991) Tribal placement of *Marshallia* (Asteraceae) using chloroplast DNA restriction site mapping. *American Journal of Botany*, **78**, 1028–1035.
- White TA, Campbell BD, Kemp PD, Hunt CL (2000) Sensitivity of three grassland communities to simulated extreme temperature and rainfall events. *Global Change Biology*, **6**, 671–684.
- Wigley TML (2009) The effect of changing climate on the frequency of absolute extreme events. *Climatic Change*, **97**, 67–76.

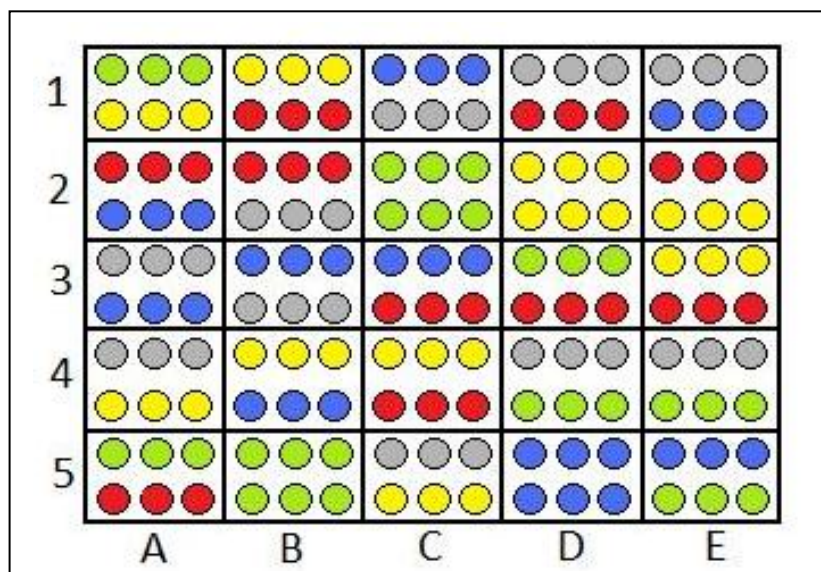
- Williams AL, Wills KE, Janes JK, Vander Schoor JK, Newton PCD, Hovenden MJ (2007) Warming and free-air CO₂ enrichment alter demographics in four co-occurring grassland species. *New Phytologist*, **176**, 365–374.
- Williams JW, Jackson ST, Kutzbach JE (2007) Projected distributions of novel and disappearing climates by 2100 AD. *Proceedings of the National Academy of Sciences of the United States of America*, **104**, 5738–5742.
- Wilson RJ, Gutiérrez D, Gutiérrez J, Martínez D, Agudo R, Monserrat VJ (2005) Changes to the elevational limits and extent of species ranges associated with climate change. *Ecology Letters*, **8**, 1138–1146.
- Woodward G, Benstead JP, Beveridge OS, *et al.* (2010) Ecological networks in a changing climate. *Advances in Ecological Research*, **42**, 71–138.
- Wu Z, Dijkstra P, Koch GW, Peñuelas J, Hungate BA (2011) Responses of terrestrial ecosystems to temperature and precipitation change: a meta-analysis of experimental manipulation. *Global Change Biology*, **17**, 927–942.
- Yang H, Wu M, Liu W, Zhang Z, Zhang N, Wan S (2011) Community structure and composition in response to climate change in a temperate steppe. *Global Change Biology*, **17**, 452–465.
- Zavaleta ES, Shaw MR, Chiariello NR, Mooney H a, Field CB (2003) Additive effects of simulated climate changes, elevated CO₂, and nitrogen deposition on grassland diversity. *Proceedings of the National Academy of Sciences of the United States of America*, **100**, 7650–7654.
- Zeiter M, Stampfli A, Newbery DM (2006) Recruitment limitation constrains local species richness and productivity in dry grassland. *Ecology*, **87**, 942–951.
- Zhu K, Woodall CW, Clark JS (2012) Failure to migrate: lack of tree range expansion in response to climate change. *Global Change Biology*, **18**, 1042–1052.
- Ziska LH (2003) Evaluation of the growth response of six invasive species to past, present and future atmospheric carbon dioxide. *Journal of Experimental Botany*, **54**, 395–404.
- Zobel M, Kalamees R (2005) Diversity and dispersal - can the link be approached experimentally? *Folia Geobotanica*, **40**, 3–11.

7. Supplementary Materials

Supplementary Material 1. Calibration curve used for converting values of soil moisture measured in arbitrary units (x axis) to the percentage of volumetric water content (m^3/m^3 , y axis). TST1 correspond to used TMS dataloggers.



Supplementary Material 2. Random distribution of studied species in 25 six-well culture plates across the temperature gradient. Temperature decreases from A to E. Green color represents *S. inaequidens*, yellow *T. procumbens*, red *S. jacobaea*, blue *S. viscosus* and gray *G. ciliata*.



Supplementary Material 3. Species abbreviations used in the ordination diagrams.

AgroStol - *Agrostis stolonifera*, *AjugRept* - *Ajuga reptans*, *AlopPrat* - *Alopecurus pratensis*, *AnemNemo* - *Anemone nemorosa*, *ArrhElat* - *Arrhenatherum elativ*, *BellPere* - *Bellis perennis*, *BromMoli* - *Bromus molis*, *CalaEpig* - *Calamagrostis epigejos*, *CapsBurs* - *Capsella bursa-pastoris*, *CeraGlom* - *Cerastium glomeratum*, *CeraHolo* - *Cerastium holosteoides*, *CirsArve* - *Cirsium arvense*, *DactGlom* - *Dactylis glomerata*, *DigiSang* - *Digitaria sanguinalis*, *EchinCrus* - *Echinochloa crus-galli*, *ElytRepe* - *Elytrigia repens*, *EragMino* - *Eragrostis minor*, *ErigAcri* - *Erigeron acris*, *ErodCicu* - *Erodium cicutarium*, *FestPrat* - *Festuca pratensis*, *FestRubr* - *Festuca rubra*, *GaliCili* - *Galinsoga ciliata*, *GaliAlbu* - *Galium album*, *GaliApar* - *Galium sarine*, *GeraPuss* - *Geranium pusillum*, *GeraPyre* - *Geranium pyrenaicum*, *GeumUrba* - *Geum urbanum*, *GlechHede* - *Glechoma hederacea*, *HypePerf* - *Hypericum perforatum*, *HypoRadi* - *Hypochaeris radista*, *ChenoAlbu* - *Chenopodium album*, *LactSerr* - *Lactuca serriola*, *LamiPurp* - *Lamium purpureum*, *LeonAutu* - *Leontodon autumnalis*, *LeonHisp* - *Leontodon hispidus*, *LoliPere* - *Lolium perene*, *MalvNegl* - *Malva neglecta*, *MatrDisc* - *Matricaria discoidea*, *MediLupu* - *Medicago lupulina*, *OxalCorn* - *Oxalis corniculata* var. *Repens*, *PersLapa* - *Persicaria lapathifolia*, *PhlePrat* - *Phleum pretense*, *PlanLanc* - *Plantago lanceolata*, *PlantMajo* - *Plantago major*, *PoaAnnua* - *Poa annua*, *PoaPrate* - *Poa pratensis*, *PoaTrivi* - *Poa trivialis*, *PolyAvic* - *Polygonum aviculare*, *PortOler* - *Portulaca oleracea*, *PoteRept* - *Potentilla reptans*, *PrunVulg* - *Prunella vulgaris*, *RanuRepe* - *Ranunculus repens*, *RobiPseu* - *Robinia pseudoacacia*, *RorrAust* - *Rorripa austriaca*, *RumeAcet* - *Rumex acetosa*, *RumeObtu* - *Rumex obtusifolius*, *SetaGlau* - *Setaria glauca*, *SisyOffi* - *Sisymbrium officinale*, *StelMedi* - *Stellaria media* agg., *Tara* - *Taraxacum* sect. *Ruderalia*, *TrifPrat* - *Trifolium pratense*, *TrifRepe* - *Trifolium repens*, *TripInod* - *Tripleusperrum inodorum*, *UrtiDioi* - *Urtica dioica*, *VeroArve* - *Veronica arvensis*, *VeroHede* - *Veronica hederifolia* agg., *VeroChama* - *Veronica chamaedris*, *VeroOffic* - *Veronica officinalis*, *VeroPers* - *Veronica persica*, *ViciCracc* - *Vicia cracca*

Supplementary material 4. Photos.



Fig. 1. Study site 1 and 2.



Fig. 2. Study site 3.



Fig. 3. Temperature gradient table.

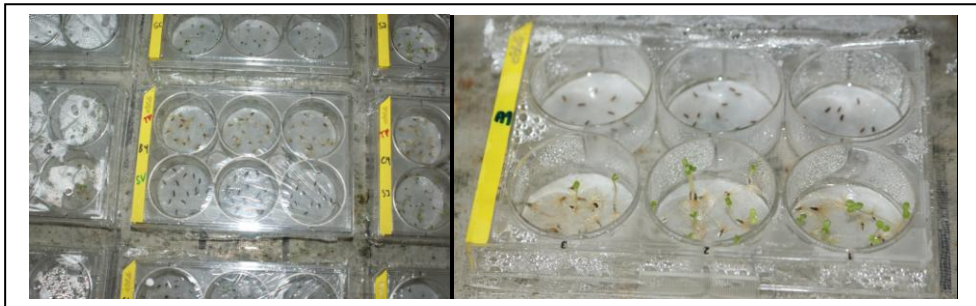


Fig. 4. Detail of six-well culture plates used for germination of studied species under the temperature gradient.



Fig. 5. Sowing plots above and outside the pipeline.



Fig. 6. Detail of sowing plots above the pipeline (upper) and outside the pipeline (bottom).



Fig. 7. Seedlings of studied species (*S. jacobaea*, *T. procumbens*, *G. ciliata*, *S. inaequidens*) in a field experiment.



Fig. 8. Flowering *G. ciliata*, *T. probumbens*, and *S. viscosus*.