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Sainfoin (*Onobrychis viciifolia*) a legume with great ecological and agronomical potential under climate change

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Abstract

Climate change is a global challenge to ecosystem services, altering crop yields and food security worldwide. In the context of climate change, *Onobrychis viciifolia* Scop. (sainfoin) can offer a multitude of ecosystem services conferred by its multifaceted beneficial properties. We reviewed the morphological, biochemical and physiological responses to environmental stressors of *O. viciifolia*, summarized its ecological, agronomic, nutritional and biological interests, and we discussed its use under climate change. *Onobrychis viciifolia* is a hemicryptophyte forage legume adapted to arid and semiarid regions by evolving a diverse array of protective mechanisms against abiotic stressors at morphological, biochemical and physiological levels. In the present scenario of climate change, *O. viciifolia* has desirable forage characteristics such as high nutritive value, high voluntary intake and palatability to grazing animals, leading to satisfying animal performance for milk, meat, honey and wool production. Recent studies suggest that *O. viciifolia* has several highly beneficial phytochemical properties including condensed tannins and polyphenol content, which have been demonstrated to have anthelmintic activities, enhance protein utilization, and prevent bloating. In addition, *O. viciifolia* also has the potential to reduce greenhouse gas emissions and sequestrate atmospheric carbon and nitrogen into the soil. Ethnobotanical investigations show that *O. viciifolia* possesses antimicrobial, antiseptic and vulnerary activities. This review could be helpful for understanding of *O. viciifolia* characteristics, interests and uses, thus promoting its reasonable cultivation under a changing climate.

Introduction

Global climate change has become a compelling environmental problem as it is hindering the yield performance of crops due to increasing environmental stresses including pest diseases and extreme climatic events (Jiang *et al*., 2016; Zhang *et al*., 2019*a*; Bakala *et al*., 2021; Skendžić *et al*., 2021). In addition, climate change may exacerbate soil erosion (Lal, 2012) and cause disturbances to ecosystem functions (van der Geest *et al*., 2019). Ecosystems functions are the respective direct and indirect benefits arising from the ecological functioning of healthy productive ecological systems (Millennium Ecosystem Assessment, 2005; Beaumont *et al*., 2007). Crop yields are projected to decline through the 21st century (Zinyengere *et al*., 2013; Petersen, 2019) and there is a need to identify and characterized perennial forage legumes that would be able to stand high environmental stress levels while offering relatively high agronomic production (Seo and Mendelsohn, 2008; Komainda *et al*., 2019). Moreover, ecological restoration of degraded lands is included in the array of adaptation and mitigation responses to climate change (Harris *et al*., 2006; O'Mara, 2012; Simonson *et al*., 2021).

The genus *Onobrychis* Miller (Fam. Fabaceae) comprises a few agronomically known forage legume species such as *O. transcaucasica* Grossh., *O. arenaria* (Kit.) DC. and *O. viciifolia* Scop. (sainfoin), the most commonly cultivated species of the genus (Lock, 2005; Mabberley, 2008; Amirahmadi *et al*., 2014). *Onobrychis viciifolia* has a long history of traditional cultivation in Europe, Asia and North America in the 19th and 20th centuries (Miller and Hoveland, 1995; Frame *et al*., 1998). Indeed, its cultivation decline started in the middle of the 20th century due to the adoption of more intensive farming methods with the introduction of relatively low-cost nitrogen (N) fertilizers (Carbonero *et al*., 2011). Consequently, *O. viciifolia* cultivation was gradually displaced by alfalfa (*Medicago sativa* L.) and clover species (*Trifolium* spp.) whose higher yields and easier establishment made them more desirable to farmers. *Onobrychis viciifolia* can be cultivated in multitude soils and climatic conditions (Tufenkci *et al.*, 2006; Carbonero *et al.*, 2011; Yin *et al.*, 2020). Agronomically, *O. viciifolia* have positive characteristics such as a deep tap root that allows it to be very tolerant to drought (Irani *et al.*, 2015*a*, 2015*b*; Malisch *et al.*, 2016) and N fixation up to 168 kg N_2/ha via symbiosis with rhizobia (Malisch *et al.*, 2017). Culture trials of *O. viciifolia* under harsh climatic conditions of dry areas in the Middle East and North Africa (MENA) region gave promising results (Le Houérou, 1969; Jafari *et al.*, 2014; Sayar *et al.*, 2022). In addition, *O. viciifolia* is also particularly valued for its content of condensed tannins, which have been shown to improve animal growth and health (Waghorn, 2008; Girard *et al.*, 2016).

The Mediterranean Basin has been identified as one of the most climate-vulnerable regions and a climate change ‘hotspot’ (Salvia *et al.*, 2021). In addition, the Mediterranean Basin is one of the areas with the most serious soil degradation and desertification rates in the world, reaching critical limits for its ability to provide ecosystem services and land productivity (Ferreira *et al.*, 2022). In this sense, the large-scale grassland degradation in Mediterranean Basin aggravates the shortage of forage supply (Ferreira *et al.*, 2022; Soares *et al.*, 2022). Consequently, restoring degraded grasslands and increasing forage grass supply are urgent needs in this area, but the forage quality of *O. viciifolia* has not been deeply studied in the Mediterranean Basin. Additionally, *O. viciifolia* has obvious application advantages in soil and vegetation restoration that should be also analysed in detail in the Mediterranean Basin.

The study of *O. viciifolia* has regained interest in recent decades (Fig. 1) and four studies have reviewed its cultivation and agronomic potential (Carbonero *et al.*, 2011; Bhattarai *et al.*, 2016; Mora-Ortiz and Smith, 2018; Sheppard *et al.*, 2019). However, no work has focussed on the role of *O. viciifolia* in the present scenario of climate change. In this work, we review the geographical distribution, main functional traits, stress tolerance and beneficial proprieties for humans of *O. viciifolia* under the ongoing climate change scenario. Our review is meant to provide information on the importance of *O. viciifolia* for its possible utilization in cropping systems in a changing environment. Also, it is an attempt to recognize the lesser-explored aspects and knowledge gaps in the research on *O. viciifolia*.

Methods

Google Scholar, Web of Science, Springer and PubMed databases were used to search for published literature on *O. viciifolia*. The filtering was based on titles, abstracts and keywords including the words *Hedysarum onobrychis* L., *Onobrychis sativa* Lam., *Onobrychis viciaefolia* Scop. and *O. viciifolia* Scop. or sainfoin. Afterwards, the full text of all peer reviewed articles, books, book chapters and PhD thesis were reviewed. The deadline for the literature selected was up to July 2024. The Plant List (http://www.theplantlist.org/tpl1.1/search?q=Onobrychis+viciifolia), International Plant Name Index (https://www.ipni.org/n/510168-1), Kew Botanical Garden (https://powo.science.kew.org/taxon/urn:lsid:ipni.org:names:510168-1) and Global Biodiversity Information Facility (https://www.gbif.org/fr/species/2972595) were used for validating the scientific name as well as information on cultivars and the species synonyms.

Origin and distribution

Onobrychis viciifolia is derived from the natural hybridization between *O. arenaria* and *O. montana* (Falistocco, 1991), which are native to Central-Southern Europe, and temperate Southwest Asia and North Africa, respectively (Angevain and Prosperi, 1995; Jin *et al.*, 2021). *Onobrychis viciifolia* is mostly tetraploid, through there are reports of diploid accessions (Carbonero *et al.*, 2013). In addition, Abou-El-Enain (2002) reported the appearance of $2n = 22$, 27, 28 and 29 chromosomes that demonstrated the role of aneuploid alterations in the evolution of this species.

A few *Onobrychis* taxa, such as *O. viciifolia*, have been cultivated for hundreds of years as forage and ornamental crops in warm and temperate regions of Europe, Asia and North

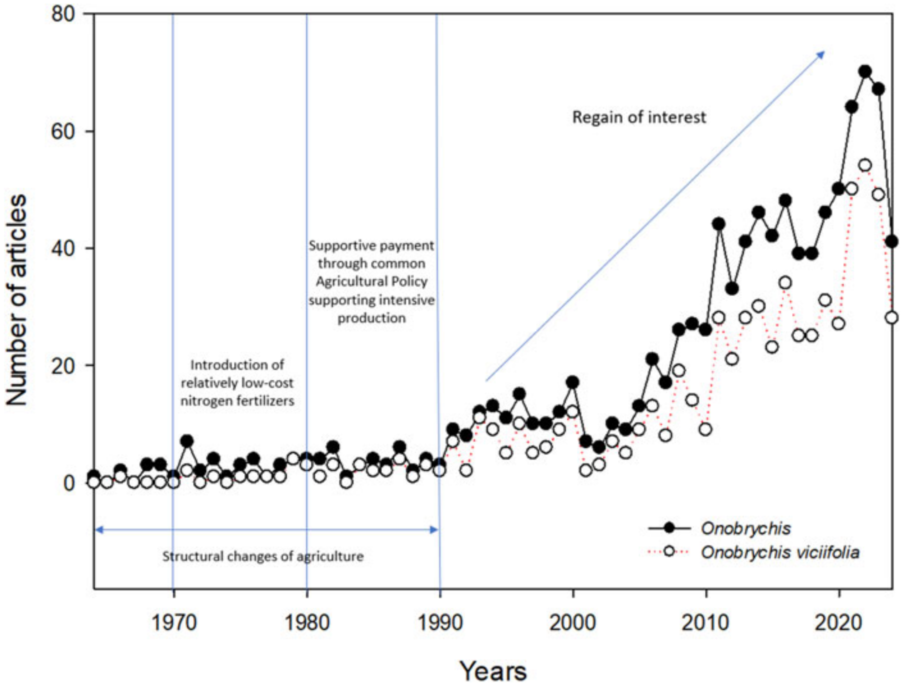

Figure 1. Evolution of annual number of publications on *Onobrychis* species and *O. viciifolia* published from 1963 to 2024 (Sources: Google Scholar, Web of Science, Springer and PubMed).

America (Lock and Simpson, 1991; Yakovlev *et al.*, 1996; Mabberley, 1997; Frame *et al.*, 1998; Frame, 2005; Carbonero *et al.*, 2011) (Fig. 2). Cultivated *Onobrychis* species were introduced to Central Europe from the Mediterranean Basin during the 16th century (Piper, 1924; Burton and Curley, 1968). *Onobrychis* cultivation was introduced to North America in 1786 (Bhattarai *et al.*, 2016), but was only grown occasionally until the 1960s, when improved varieties allowed wider cultivation. Today, *O. viciifolia* is cultivated mainly in Eastern Europe, Iran and around the Mediterranean Basin (Eken *et al.*, 2004; Avci *et al.*, 2014; Bolat, 2019). The Mediterranean Basin is one of the most affected regions by climate change (Cammarano *et al.*, 2019). One of the most relevant consequences of climate change is certainly water scarcity, as result of a reduction of surface runoff and groundwater levels (Noto *et al.*, 2023). *Onobrychis viciifolia* once represented an important forage legume in semi-arid environments of Italy, but its cultivation area has decreased from 160 to 9 thousand ha from 1983 to 2013 (ISTAT, 2013). It is recorded that more than 150 tonnes of seeds were sold every year in the late 1950s in the UK, enough for cropping 2500 ha (Hill, 1997). In the late 1970s, only approximately 150 ha were cropped. Today, *O. viciifolia* has become rare in the UK, and this is due, in part, to its poor response to the changing requirements and circumstance of British agriculture (Hutchinson, 1966). *Onobrychis viciifolia* could potentially be grown on 950 thousand ha in England and Wales, where the soil is sufficiently alkaline (Doyle *et al.*, 1984). On the other hand, Wang *et al.* (2018) mentioned *O. viciifolia* as a major fodder grass species cultivated in Gansu Province, Northwest China, in 2016.

Responses to environmental stressors

Biotic stressors

Ongoing climate change poses considerable threats to sustainable food security, including increased number of generations of pests and plant pathogens resulting from a compressed life cycle due to a warmer climate combined to elevated CO_2 concentrations, increased risk of invasion by migratory pests and reduced effectiveness of biological control (Skendžić *et al.*, 2021). As climate change exacerbates the pest problem, there is a great need for future pest management strategies (Wei *et al.*, 2020). *Onobrychis viciifolia* is relatively resistant to most common pests and diseases in Western Canada and Northern Europe compared with other legumes such as *M. sativa* (Goplen *et al.*, 1991; Frame *et al.*, 1998). This has been attributed to the presence of a range of secondary metabolites, such as tannins and polyphenols, within the foliage of *O. viciifolia* (Malisch *et al.*, 2016). Even so, *O. viciifolia* can be damaged by fungal diseases related to certain *Fusarium*, *Stemphyllium* and *Sclerotinia* species (Mathre, 1968). In addition, an important number of insect and nematode species can damage *O. viciifolia* stands (Mathre, 1968; Wallace, 1968; Morrill *et al.*, 1998). But *O. viciifolia* is resistant to the alfalfa weevil (*Hypera postica* Gyll.), so it can be an alternative forage legume to *M. sativa* in areas where this pest causes severe damage (Morrill *et al.*, 1998; Böttger *et al.*, 2013).

Onobrychis viciifolia is relatively resistant and free from serious pest and disease problems compared with other legumes such as *M. sativa* (Goplen *et al.*, 1991). *Medicago sativa* suffers from several economically important insect pests such as *H. postica* and

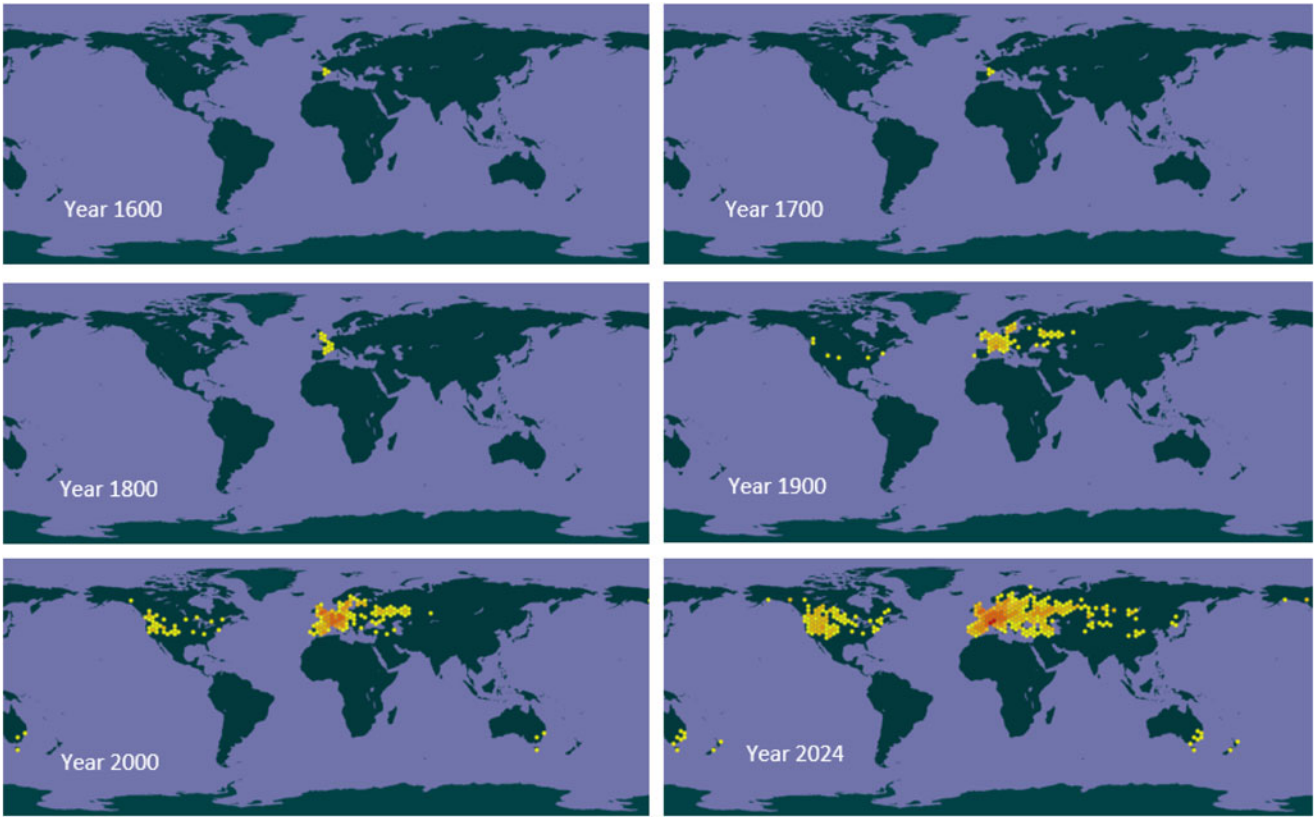

Figure 2. Centenary evolution of worldwide geographical distribution of *Onobrychis viciifolia* (88.635 occurrences) from 1600 to 2024. The colours from yellow to orange represent the density of occurrence for a given area.
Source: Global Biodiversity Information Facility, https://www.gbif.org/

Acyrthosiphon pisum, which do not affect *O. viciifolia*. This could encourage farmers to grow *O. viciifolia* as an alternative solution to *M. sativa* (Morrill *et al.*, 1998). Two closely related species to *H. postica* (*Phytonomus farinosus* and *Hypera trilineata*) are mentioned as pests of *O. viciifolia* in some European countries (Wallace, 1968). Other pests such as *Empoasca fabae*, *Lygus elisus*, *L. hesperus* and *Adelphocoris lineolatus* appeared to have marginal effects on *O. viciifolia* and occurs only in localized areas (Morrill *et al.*, 1998). Furthermore, only one pest (*Sitona scissifrons*), which feed on the roots of *O. viciifolia*, has been observed on accessions growing in United Kingdom, but there were no accessions that were severely affected (Carbonero *et al.*, 2011). Adult *S. scissifrons* weevils become active in the field in June and eat the edges of the leaves of *O. viciifolia*, leaving characteristic notches along the leaves in Montana (USA). This damage could be disastrous at the seedling stage in the field (Wallace, 1968). Other members from this genus, including *S. lineata*, *S. calloso* and *S. crinite*, have been reported to cause minor damage in *O. viciifolia* in Europe (Wallace, 1968). However, *Contarinia onobrychidis* and *Eurytoma onobrychidis* represent a serious pest for *O. viciifolia* in some areas of Europe (Wallace, 1968). Other insects can also damage the seed production of *O. viciifolia* in Europe but marginally; these include *Perrisia onobrychidis*, *Apion pisi*, *Odontothrips intermedius*, *Otiorhynchus ligustici* and *Melanotus erythropus*. Therefore, the inclusion of *O. viciifolia* as a rotation component could affect the presence of host-specific pests by disturbing their life cycle.

Abiotic stressors

Climate change is increasing the frequency and intensity of abiotic stress combinations that pose a serious threat to crop productivity (Zandalinas *et al.*, 2022). *Onobrychis viciifolia* have evolved a diverse array of protective mechanisms against abiotic stressors at biochemical and physiological levels related to hormone homoeostasis, transcriptional factors, photosynthesis, and the biosynthesis of antioxidants and osmotic adjustment-related substances (Yin *et al.*, 2021). Consequently, *O. viciifolia* tolerates low nutrient conditions (Carbonero *et al.*, 2011), high levels of active lime in the soil (De Falco *et al.*, 2000*a*, 2000*b*), drought and alkalinity, and saline-alkaline stress (Fig. 3). In addition, *O. viciifolia* tolerates high concentrations of lead and copper (Beladi *et al.*, 2011) and can grow in coal mined areas (Roy *et al.*, 2021). Moreover, *O. viciifolia* can grow under seasonally cold and hot climatic conditions (Sengul, 2003; Tufenkci *et al.*, 2006), and extreme climatic conditions at high altitudes (Yin *et al.*, 2020, 2021). Rhizobia have the potential to be used in improving symbiotic N fixation on *O. viciifolia* under cold stress (Prévost *et al.*, 2003). Climate change can affect the intensity and frequency of precipitation (Feng *et al.*, 2019) and worsen ozone pollution over many populated regions, with larger impacts at higher concentrations (East *et al.*, 2024). It has long been observed that the environmental gamma-ray dose rate increases noticeably during precipitation intervals (Mercier *et al.*, 2009). *Onobrychis viciifolia* tolerates high levels of gamma radiation (Beyaz *et al.*, 2016), but its growth is reduced after ozone exposure (Bungener *et al.*, 1999).

Salt tolerance

Salt is one of the main abiotic stresses affecting crop yields around the world (Zörb *et al.*, 2019). Seed germination is one of the most sensitive physiological phenomena to stress in the lifecycle of plants (Al-Turki *et al.*, 2022), and seeds of *O. viciifolia* withstand moderate saline environments (up to 400 mM). In this sense, seeds of *O. viciifolia* retain germinability under high salinity, displaying tolerance mechanisms such as physiological dormancy till the occurrence of favourable conditions (Li *et al.*, 2021*a*, 2021*b*). Karamian and Ataei-Barazande (2013) reported decreasing germination rates in *O. viciifolia* with increasing salinity levels over 200 mM NaCl and indicated that germination was totally inhibited at 400 mM NaCl which is higher than for *Trifolium repens* L. (up to 180 mM) (Chu *et al.*, 2022), *Trifolium pratense* L. (up to 240 mM) (Asci, 2011) and *M. sativa* (up to 257 mM) (Kadri *et al.*, 2021). The germination of *O. viciifolia* is considered more tolerant to salinities c. 170 mM NaCl than other *Onobrychis* species (Uzun *et al.*, 2017).

Saline-alkaline conditions resulted in oxidative stress and the accumulation of proline in seedlings of *O. viciifolia* (Wu *et al.*, 2021). Along with organic osmolytes, *O. viciifolia* under salinity also increased the production of reactive oxygen species (ROS) scavengers such as catalase, superoxide dismutase, glutathione reductase and ascorbate peroxidase (Beyaz, 2019). In fact, *O. viciifolia* can grow without much yield and quality loss in salt-affected areas (c. 109 mM NaCl), where it can provide enough high-quality forage production for livestock without altering its macro-mineral content (Temel *et al.*, 2016*a*, 2016*b*) (Fig. 3a). Nonetheless, Wu *et al.* (2017*a*, 2017*b*) reported reduced growth and chlorophyll and water contents, diminished root potassium concentration, and increased malondialdehyde (MDA) concentration and relative membrane permeability in *O. viciifolia* shoots under salinity (100 mM NaCl). This study also reported that, when supplied exogenously, proline and silicon improved salt stress tolerance in *O. viciifolia* by mitigating sodium toxicity (Fig. 3a). Under salinity, *O. viciifolia* maintain better cellular function and overall physiological homoeostasis evidenced by less drastic imbalance in intracellular Na^+/K^+ ratio than *M. sativa* (Li *et al.*, 2010; Beyaz 2019) which is one of the key determinants of plant salt tolerance under climate change (El Sabagh *et al.*, 2021).

Drought tolerance

Drought is the largest contributor to world-wide crop losses (Lesk *et al.*, 2016; Santos-Medellín *et al.*, 2021). In this general context that is exacerbated by climate change (Cook *et al.*, 2018), *O. viciifolia* produces indehiscent fruits (pods) that break down slowly, promoting seed survivorship during drought periods (Majidi and Barati, 2011; Avci and Kaya, 2013). In this sense, organic, hydrogel and mineral seed coating improved germination speed of *O. viciifolia* with and without drought (Mehrabi and Chaichi, 2012). Contradictorily, Kintl *et al.* (2021) showed that *O. viciifolia* did not respond positively to the seed coating under drought. Uncoated seeds exhibited a greater drought resistance than the coated seeds which showed a sharp, significant decline of germination capacity and a great increase in the dead seed percentage due to the death of a fraction from the hard seeds.

Nasirzadeh *et al.* (2005) reported that *O. viciifolia* can be considered as a semi-resistant species to drought. Adult plants of *O. viciifolia* tolerate exposure to the combined effects of drought and ozone (Bungener *et al.*, 1999). The response mechanisms of *O. viciifolia* to drought include osmotic adjustment (Dehabadi, 1997; Irani *et al.*, 2015*a*, 2015*b*; Beyaz, 2019; Beyaz and Yildiz, 2021), ROS scavenging, reduced transpiration (Roy *et al.*, 2021), increasing stomatal resistance and water use efficiency (Dehabadi *et al.*, 1993*a*, 1993*b*; Dehabadi, 1997; Huang

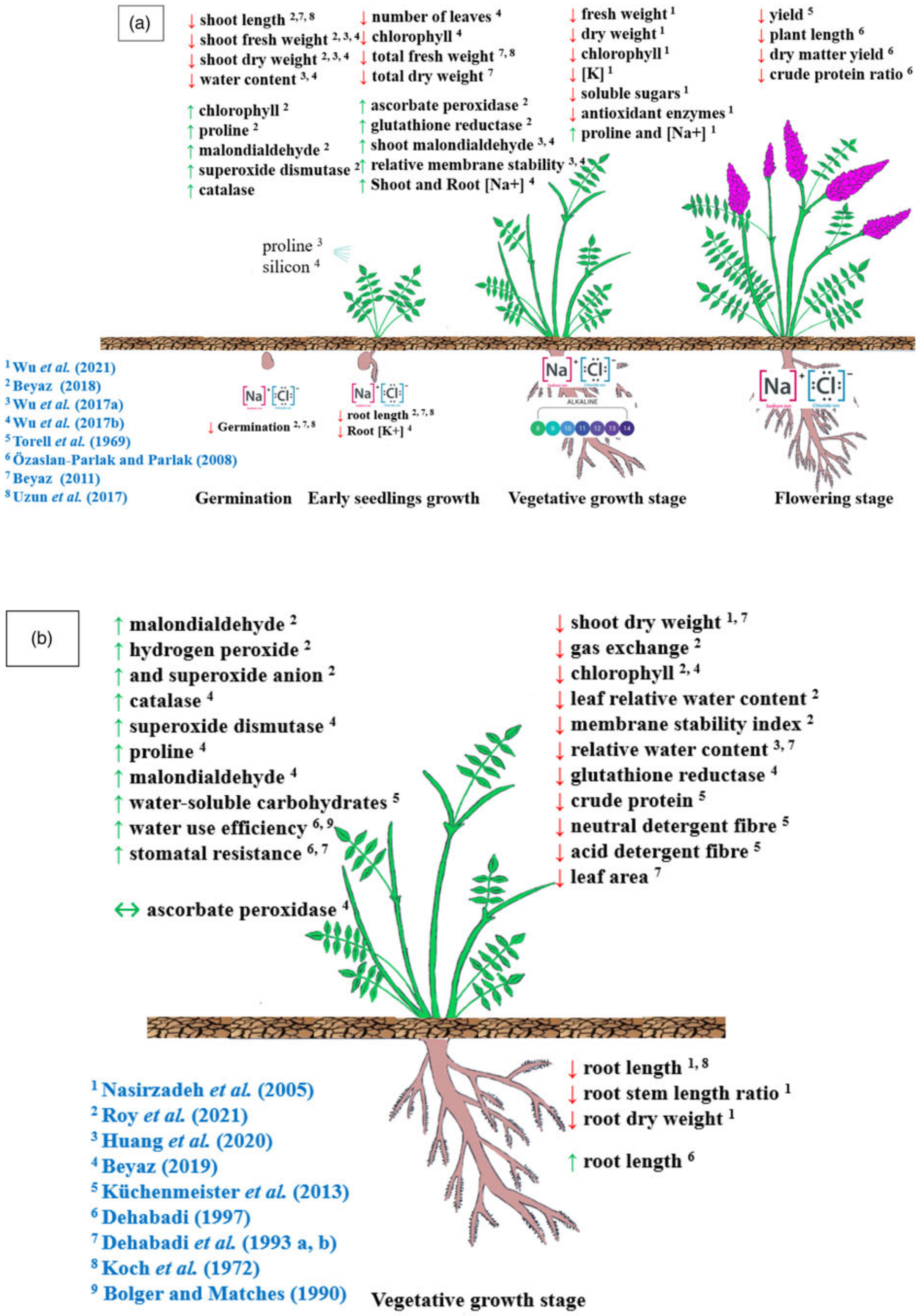

Figure 3. Summary of the main tolerance mechanisms of *Onobrychis viciifolia* to (a) salinity and (b) drought stress.

et al., 2020), and increasing carotenoid contents with decreasing chlorophyll contents (Irani *et al.*, 2015*a*, 2015*b*). In addition, *O. viciifolia* tolerance to drought involves also morphological adaptations such as a deep root system (Koch *et al.*, 1972; Dehabadi, 1997; March-Salas *et al.*, 2021) and reduced leaf area (Dehabadi *et al.*, 1993*b*). Besides all its responses to drought, *O. viciifolia* shows reduced plant heights which resulted in significant yield losses when exposed to severe drought (Irani *et al.*, 2015*a*, 2015*b*). In this sense, Bolger and Matches (1990) found a higher yield potential for *O. viciifolia* in spring than in summer, possibly indicating higher water use efficiency. To tide over periodic drought stress, Malisch *et al.* (2016) highlighted the importance of harvesting at optimal stages to have good forage performance for *O. viciifolia*.

Onobrychis viciifolia have greater ability to resist drought and adapt to dry habitats compared to several forage species. Considering the field capacity as the upper limit of soil water availability, *O. viciifolia* had the widest range of adaptability to soil water compared to other crop species such as *Astragalus adsurgens*, *Elymus nutans* and *Lolium multiflorum* (Huang *et al.*, 2020). Moreover, *O. viciifolia* exhibited a lower average lower limit of relative soil water content compared to *A. adsurgens*, *E. nutans*, and *L. multiflorum*. In addition, *O. viciifolia* closed stomata more rapidly with the decrease of relative soil water content, suggesting that the species had better drought resistance and allowed plants to keep water in plant tissues (Huang *et al.*, 2020). The intrinsic water use efficiency (WUE_i) represents an important indicator of the adaptability for higher plants to climate change (Weiwei *et al.*, 2018). WUEi increased more rapidly in *O. viciifolia* than the other three forage under moderate water deficit (Huang *et al.*, 2020).

High temperatures tolerance

Onobrychis viciifolia is an alternative forage for semi-arid regions, where *M. sativa* and *Trifolium* sp. cannot be sown. Although there is little published data, there is considerable observational evidence that *O. viciifolia* is tolerant to relatively high temperatures. Maximum air temperatures of above 32°C did not affect *O. viciifolia* in small plots in northern Greece and southern Spain (Carbonero *et al.*, 2011). However, *O. viciifolia* exhibits poor growth following periods of high ambient temperatures and few plants survived at 35°C due to severe leaf loss causing plant death because high metabolic rates cannot be supported by existing leaf area or taproot carbohydrates even under well-watered conditions (Kallenbach *et al.*, 1996). High temperatures at the beginning of summer interrupt regrowth under traditional and intensive cutting regimes in southern Italy (De Falco *et al.*, 2000*a*, 2000*b*). *Onobrychis viciifolia* had a higher rate of biomass accumulation compared to *M. sativa*. However, *M. sativa* tended to grow faster during the warmer months (July–September) in Texas (USA).

Interests and uses

Agronomic characteristics and value

Changing climatic conditions have reduced plant productivity and generated food security issues. In this context of food security, legumes exhibit promising benefits making them an exceptional food to meet nutritional needs (Akram *et al.*, 2018). *Onobrychis viciifolia* is considered as an excellent component of a rotation in cropping systems by enhancing productivity and improving soil physicochemical properties including soil texture, fertility, water retention and organic matter content (Decourtye *et al.*, 2007; Malisch *et al.*, 2017; Sariyildiz and Savaci, 2020).

Agronomic advantages

Global climate change is predicted to impact on soil fertility through the physical, chemical, and biological properties of soil due to rise in temperature, alternation in precipitation patterns, increase in greenhouse gases concentration in the atmosphere, etc. (Mondal, 2021; Bibi and Rahman, 2023). In addition, climate change could lead to the loss of soil function for fertility maintenance and greater dependence on mineral fertilizers (Pareek, 2017). For centuries, *O. viciifolia* was widely grown across Europe before commercial fertilizers were used. The species does not need fertile soil to thrive if its requirements for lime and humidity are satisfied. *Onobrychis viciifolia* can thrive in less fertile soils than *M. sativa* and *T. repens* and can also grow well in more fertile soils. *Medicago sativa* and *T. repens* will, however, produce better yields in fertile and irrigated lands, but *O. viciifolia* provides better outcomes growing in low fertility soils compared with *M. sativa* (Benaiges, 1971; Demdoum, 2012).

Mature plants of *O. viciifolia* have over 2-m-long taproots, partly responsible for its drought tolerance. The root is quite branched, especially at the bottom and multiples thin lateral roots constitute the bulk of the root system (Carbonero *et al.*, 2011; Mora-Ortiz and Smith, 2018). The *O. viciifolia* root systems rivals *M. sativa* for its ability to access deep subterranean waters (Mora-Ortiz and Smith, 2018). In the Mediterranean Basin, *O. viciifolia* prefers altitudes above 600 m, but it performs well when cultivated in a range between 100 and 2500 m (García Salmerón *et al.*, 1966; Demdoum, 2012).

Agronomic disadvantages

Onobrychis viciifolia is a forage legume of renewed interest worldwide, with equally weighted advantages and disadvantages that prevent many farmers from considering this crop a viable alternative to other forage legumes. In this sense, a wide distribution of *O. viciifolia* in productive grassland systems is hampered by the limited availability of high-performing cultivars adapted to different environmental conditions (Subedi, 2018; Sheppard *et al.*, 2019). In fact, *O. viciifolia* weaknesses are related to its lower yield when compared to other forage legumes, its poor competitive ability against weeds especially during the establishment year, a limited persistence, susceptibility to waterlogging and frost (Sheehy and Popple, 1981; Liu *et al.*, 2010), low tolerance to frequent cutting (Malisch *et al.*, 2017), and susceptibility to diseases such as powdery mildew or *Phytophthora* root rot (Sears *et al.*, 1975; Carbonero *et al.*, 2011). *Onobrychis viciifolia* prefers well-drained soils and does not grow well in heavy soils or under flood irrigation (García Salmerón *et al.*, 1966; Demdoum, 2012; Anderson, 2016). *Onobrychis viciifolia* does not perform properly in acidic soils. Poor *O. viciifolia* establishment was obtained on soils at pH lower than 6 (Bland, 1971; Carbonero *et al.*, 2011). In Spain, *O. viciifolia* is traditionally cultivated on neutral or slightly alkaline brown-earth soils.

Onobrychis viciifolia died out primarily during winter due to aerial interspecific competition, resulting in reduced root reserves (Liu *et al.*, 2010). Persistence of *O. viciifolia* appears to be dependent on minimal pressure from competing plants, harvest or grazing, and good growth conditions from midsummer into fall, allowing for adequate root reserves for survival. It is possible that judicious use of glyphosate in late season might lessen competition in that critical period as *O. viciifolia* is more glyphosate-tolerant than *M. sativa* (Peel *et al.*, 2013).

Crop residue

Due to its deep, extensive and nodulated roots system, *O. viciifolia* uses water reserves in deep soil layers, increases carbon sequestration, reduces moisture and nutrient loss through leaching and runoff, prevents soil erosion, and improves the physicochemical and microbiological properties of the soil, including reductions on nitrification rates (Sergeeva, 1955; Komainda *et al.*, 2019; Clemensen *et al.*, 2022). The irrigated cultivation of *O. viciifolia* accumulate in the soil up to 16.2 t/ha/year of residues, which represents approximately four times the quantity left by *M. sativa* (4.2 t/ha/year) (Sergeeva, 1955). This could be explained by its high root biomass compared to other cultivated legumes (Bolat, 2019; Rossi *et al.*, 2020). In fact, *O. viciifolia* can be used for soil organic matter improvement (Porqueddu *et al.*, 2000; Wu *et al.*, 2018). In view of these studies, cultivating *O. viciifolia* would help increasing the role of agricultural soils as carbon sinks to mitigate climate change.

In addition to supplies biologically fixed N_2, *O. viciifolia* displays a range of adaptations for the acquisition and retention of other important resources. *O. viciifolia* has excellent resource use efficiency in low input environments (Carbonero *et al.*, 2011). By virtue of their large active root systems and mycorrhization, *O. viciifolia* can efficiently accelerate the absorption of water and nutrients (Kong *et al.*, 2014). *Onobrychis viciifolia* has the ability to acquire phosphorous via specialized root structures, through arbuscular mycorrhizal associations under controlled environment (Kong *et al.*, 2014). The large rooting systems of *O. viciifolia* function to increase soil organic C by reducing erosion, reducing microbial respiration (via lack of tillage). As a result, nutrients are retained in the cropping system for use by subsequent crops (Carbonero *et al.*, 2011).

Fossil fuel burning in the energy sector is a major contributor to greenhouse gas emissions. Biofuels, considered as a substitute for fossil fuels, have become top priority due to its eco-friendly nature (Prasad *et al.*, 2020). In addition to the biodiesel production from the legume (Ndukwu and Onyeoziri, 2022), all the biomass of *O. viciifolia* can serve to produce second-generation biofuel due to its high N content (Slepetys *et al.*, 2012). Moreover, the use of *O. viciifolia* showed potential for methane production in biogas plants (Hunady *et al.*, 2021).

Onobrychis viciifolia contains phenolic compounds (tannins) that can influence soil nutrient dynamics by inhibiting microbial activity, which could slow N mineralization rates and minimize N losses in field (Clemensen *et al.*, 2020, 2022; Slebodnik *et al.*, 2019). Tannins, at low concentrations in the soil, may increase some enzyme activity (Adamczyk *et al.*, 2017), inactivate other soil enzymes, in part due to their antibiotic properties (Benoit and Starkey, 1968; Field and Lettinga, 1992; Joanisse *et al.*, 2007; Triebwasser *et al.*, 2012), and to the formation of tannin–protein complexes (Adamczyk *et al.*, 2019). Dehydrogenase enzymatic activity was reported to be higher in *O. viciifolia* than *M. sativa* sown plots (Clemensen *et al.*, 2020, 2022).

Atmospheric di-nitrogen fixation

Crop production is dependent on inorganic N and other fertilizers inputs to resupply nutrients lost as harvested grain and forage, via soil erosion/runoff, and by other natural or anthropogenic causes (Schlautman *et al.*, 2018; Bibi and Rahman, 2023). Nitrogen-fertilizers are one of the most monetary and environmentally expensive inputs in agricultural settings, which are currently more expensive than ever before (Herrera *et al.*, 2016; Adjesiwor and Islam, 2016). The mobility of applied inorganic N fertilizers results in less than 50% fertilizer N-recovery efficiency by the first crop with substantial amounts of the remaining N leaving the cropping system as N_2O and NO_3 (Crews and Peoples, 2004; Ladha *et al.*, 2005). *Onobrychis* species are soil enriching via the fixation of atmospheric N. The symbiosis between legumes and root-nodule bacteria supplies biologically fixed N to natural and agroecosystems around the globe (Crews, 1993). This form of N is directly incorporated into the growing plant, overcoming problems of low fertilizer N-recovery efficiency. *Onobrychis viciifolia* is able to provide relief from reliance on synthetic N while supplying high forage quality in low-input agricultural ecosystems (Carbonero *et al.*, 2011). While N_2 fixation in legumes is considered to have higher energy and carbon requirements than N assimilation by plants using reduction of NO_3 for growth, the energy is supplied via solar radiation rather than through fossil fuels; thus, the resulting CO_2 respired by the nodules originates though photosynthesis and is not a net contributor to atmospheric CO_2 concentrations (Crews and Peoples, 2004; Jensen *et al.*, 2012).

Onobrychis species form symbioses with bacteria belonging to the genera *Mesorhizobium*, *Rhizobium* and *Bradyrhizobium* (Baimiev *et al.*, 2007). In field conditions, Nitrogen deficiency symptoms were reported in *O. viciifolia* despite plants being abundantly nodulated, which indicates that the strain of N-fixing bacteria present was inefficient or short lived (Burton and Curley, 1968; Schneiter *et al.*, 1969), but these symptoms disappeared with time in plants nodulated by effective strains (Prévost *et al.*, 1987*a*). Small young nodules are generally the most effective in *O. viciifolia* and are scarce in early stages of growth in the field (Burton and Curley, 1968). In this sense, it seems likely that *O. viciifolia* is dependent on some mineral N at early growth stages and later growth stages benefit significantly from an effective symbiosis (Carbonero *et al.*, 2011). However, the N-fixing system of *O. viciifolia* is very sensitive to low levels of nitrate under glasshouse conditions (Hume and Withers, 1985). *Onobrychis viciifolia* can be cross inoculated by *Rhizobium* species isolated from different leguminous species (Burton and Curley, 1968; Prévost *et al.*, 1987*a*). Furthermore, inoculating *O. viciifolia* with rhizobia isolated from three arctic legume species improved biological nitrogen fixation during cold phases of the growing season (Prévost *et al.*, 1987*a*, 1987*b*). Based on acetylene reduction rates, the general effect of adding strains of *Rhizobium* to other strains of *Rhizobium* in symbiosis with *O. viciifolia* was additive (Hill, 1980). Kong *et al.* (2014) demonstrated that the inoculation of arbuscular mycorrhizal fungi can improve mycorrhizal infection rate and plant growth, accelerating the absorption of water and nutrients by the roots compared with uninoculated plants. Kon (1980) established that *O. viciifolia*, when infected with the appropriate *Rhizobium* spp. and arbuscular fungi, produced more and larger nodules and, consequently, a greater nodule dry weight and exhibited greater N_2 fixation than plants infected with only the rhizobia in a glasshouse conditions. Over two-year experiments, *O. viciifolia* fixed 106 kg N ha/year in rain-fed Mediterranean conditions, which was below the usual range of 130–160 kg N ha/year and quite far from the potential value of 270 kg N ha/year from non-Mediterranean areas (Provorov and Tikhonovich, 2003; Re *et al.*, 2014) (Table 1). Issah *et al.* (2020) quantified biological N_2 fixation using ^{15}N isotope dilution and estimated resource partitioning in *O. viciifolia* under controlled conditions. The percentage of N derived from atmosphere was

Table 1. Effective bacterial and mycorrhiza strains for *Onobrychis viciifolia* inoculation

	Origin	Variety	References
Bacteria			
Arctic N_{31}	*Astragalus alpinus*	Melrose	Prévost *et al.* (1987*b*)
Arctic N_{11}, N_{28}	*Oxytropis maydelliana*		
Temperate SM-2	*Onobrychis viciifolia* cv Melrose		
Temperate 116M15	Commercial inoculant (Nitragin Co., Milwaukee, WI)		
116A27, 116A14, 116A8, 124Z1, 124B1	Commercial inoculant (Nitragin Co., Milwaukee, WI)	Remont	Hill (1980)
NZP 5301	*Onobrychis viciifolia* cv Fakir	Fakir	Kon (1980)
Rhizobium ciceri	*Onobrychis spinacrisbi*	–	Yousef and Abdul-Karim (2012)
Arbuscular mycorrhiza			
Gigaspora magarita	–	–	Kon (1980)
Glomus fasciculata			
Glomus tenuis			

81% corresponding to estimated N contributions of 65 kg N ha/year. In view of previous works, cultivating *O. viciifolia* would help mitigating climate change through the reduction of N fertilizers and related greenhouse gasses emissions. As well, the cultivation of *O. viciifolia* would support farmers on their efforts to cope with climate change and to face increasing costs of N fertilizers.

Weed and pest control

Climate change is opening new geographic windows for disease outbreaks, insect herbivory and weed infestations in crops worldwide (Bajwa *et al.*, 2020; Gullino *et al.*, 2022). The inclusion of *O. viciifolia* can reduce number and cover of weeds in cereal fields (Cirujeda *et al.*, 2019). Mummey and Ramsey (2017) concluded that *O. viciifolia* may be a useful bridge species for improving soil conditions while allowing for weed control during restoration of invasive crested wheatgrass (*Agropyron cristatum* (L.) Gaertmn.) stands, improving conditions for native species establishment in dry rangeland in North America. In addition, *O. viciifolia* can offer a multitude of ecosystem services by supporting biodiversity and hosting important enemies of crop pests in agricultural landscapes. For example, González *et al.* (2022) found almost 147 morphospecies of hymenopteran parasitoids in *O. viciifolia* patches providing a low-cost strategy for biological pest control in *Brassica napus* L. fields. According to these studies, cultivating *O. viciifolia* would improve biological control of pests just when their impacts are growing due to climate change.

Honey production

The change in climatic conditions is bound to have an impact on the physiology, distribution and survival of bees (Le Conte and Navajas, 2008; Smoliński *et al.*, 2021). Under this scenario, conservation of honeybees remains a challenging task (Wood *et al.*, 2020). As *O. viciifolia* is self-sterile, it relies on flower visitors for cross-pollination and requires multiple visits to maximize pollination (Bogoyavlenskii, 1955, 1974; Kropacova and Haslbachova, 1969). Bee pollination of *O. viciifolia* gave an increase of seed productivity by more than 30% (Pankov, 2013). Consequently, its flowers are a rich source of pollen and nectar, attracting ten times more bees than *Trifolium repens* L. and *M. sativa* (Rosov, 1952; McGregor, 1976; Kells, 2001; Deveci and Kuvanci, 2012). *Onobrychis viciifolia* is visited by managed and indigenous pollinator insect species, including *Apis*, *Bombus* and *Osmia* in southern Alberta (Canada), Eastern Washington (USA), the British Isles (UK), Europe and Japan (Richards and Edwards, 1988; Horne, 1995; Clement *et al.*, 2006; Howes, 2007; USDA SARE, 2007; Westphal *et al.*, 2008; Taki *et al.*, 2009). Rozen *et al.* (2010) noted that *O. viciifolia* is the only pollen source for *Osmia avosetta* Warncke bees in Turkey. In addition, different studies have described a very diverse pollinator community, dominated by *Bombus* and different bee species, foraging on *O. viciifolia* in Italy, Canada, USA, Europe and Turkey (Ricciardelli d'Albore and Roscioni, 1990; Kells, 2001; Clement *et al.*, 2006; Decourtye *et al.*, 2010; Manino *et al.*, 2010; Özbek, 2011; Pearce *et al.*, 2012; Richards, 2019). Richards and Edwards (1988) found that bumblebees visited *O. viciifolia* flowers at a much greater rate than western honeybees in Canada. As previously stated, *O. viciifolia* is a good nectar and pollen source for many pollinator species and, additionally, it shows a long-lasting flowering period to offer bee pasture for western honeybees (*Apies mellifera* L.). and wild bees (Szalai, 2001). In addition, weeds in *O. viciifolia* crops are mainly represented by melliferous species in Russia (Pankov, 2014). When grown as a forage crop, *O. viciifolia* is mown late so flowering has normally finished, maximizing its value as a bee forage crop (Ayers, 1993). With a reduced number of flowers per plant under drought, *O. viciifolia* maintained similar per-flower nectar production (Phillips *et al.*, 2018). *Onobrychis viciifolia* can yield up to 400 kg/ha of honey (Howes, 2007) with a distinctive taste, smell, texture and colour (Vereshchagin *et al.*, 2015), which constitute an additional revenue (Pankov, 2012). Recently, it has been demonstrated that the caffeine present in the nectar of *O. viciifolia* reduces the infection of bumblebees (*Bombus terrestris*) by the microsporidian parasite *Nosema bombi* Fantham and Porter (Folly *et al.*, 2021). Growing *O. viciifolia* may promote a diversification of agronomic production with honeybee related products, which is key to stand the impacts of climate change (Zhang *et al.*, 2022).

Erosion control

Global warming is expected to lead to a more vigorous hydrological cycle, including more total rainfall and more frequent torrential rainfall events, which may lead to higher soil erosion in many locations worldwide (Eekhout and de Vente, 2022; Dash and Maity, 2023). Cover of *O. viciifolia* and *Rosa canina* L. provided year-round soil protection, improving the soil structure, increasing its water holding capacity and its nutrient retention in Northwest Turkey (Sariyildiz and Savaci, 2020). *O. viciifolia* enhanced soil productivity by increasing soil organic carbon, soil total N and soil organic carbon stock capacity (Sariyildiz and Savaci, 2020). Yu *et al.* (2015) highlighted the superiority of *O. viciifolia* in water retention compared to different tree and herbaceous species in China. The structural stability of the soil under *O. viciifolia* continued for a long period and the infiltration rate was high, preventing an increase of runoff with time. Reduced-tillage systems coupled with *O. viciifolia* cropping should be considered as an efficient management practice and should be improved to withstand extreme rainfall conditions. When used as ridge-furrow rainwater harvesting with mulch, *O. viciifolia* offers farmers means to address drought, water loss and soil erosion in arable lands in arid and semiarid regions (Zhang *et al.*, 2019*b*). Yüksek and Yüksek (2015) reported that plant cover of *O. viciifolia* was the main factor reducing surface runoff. Hairy leaves of *O. viciifolia* accumulate high sediment loads per leaf area, presumably, because hairs create a buffer zone of reduced water flow velocity enhancing sedimentation (Kretz *et al.*, 2020). *O. viciifolia* is used for erosion control in northwest China and Turkey (Turk and Celik, 2006; Xu *et al.*, 2006). Yakupoglu *et al.* (2021) showed that *O. viciifolia* cultivation exhibited the lowest soil losses when compared to fallow and wheat (*Triticum aestivum* L.) in Southern Turkey. *O. viciifolia* is an efficient cover crop in the conservation of soil and water, for example, in Mediterranean vineyards (Ben-Salem *et al.*, 2018). According to these studies, cultivating *O. viciifolia* would reduce carbon emissions from soils since lowering erosion also reduces soil carbon dioxide emissions (Mandal *et al.*, 2020; Ran *et al.*, 2021).

Ecological restoration

Ecological restoration is a major nature-based solution towards meeting a wide range of global development goals by improving food and water security, protecting biodiversity and promoting adaptation and mitigation of climate change (Liu *et al.*, 2020; Simonson *et al.*, 2021). The improvement of semi-arid and arid degraded lands is one of the most important uses of *O. viciifolia*, since leguminous crops naturally increase soil productivity due to their association with N fixing microbes (Singh *et al.*, 2019). In this sense, Roy *et al.* (2021) suggested that *O. viciifolia* is suitable when designing an appropriate strategy for achieving a successful revegetation of coal mined areas. Moreover, Ibragimov *et al.* (2019) highlighted the importance of the cultivation of multi-component mixtures, including *O. viciifolia*, to face desertification in Southeast Russia.

Recently, there has been growing concern over the potential impacts of global climate change on the sensitivity of weeds to herbicides. Reduced glyphosate sensitivity is projected in response to climate change (Matzrafi *et al.*, 2019). Crop tolerance to glyphosate can reduce competition from weeds, leading to potentially higher yields and increased efficiency in weed control (Raza *et al.*, 2023). *Onobrychis viciifolia* is relatively tolerant to glyphosate application. Based on the dose estimated to cause 50% mortality (LD_{50}), *O. viciifolia* seedlings are over six times, and mature plants are over 20 times, more tolerant to glyphosate than *M. sativa*. Based on the dose required to produce a 50% reduction in biomass yield (GR_{50}), glyphosate has a 10-fold greater negative impact on *M. sativa* biomass yield than it does on *O. viciifolia*. In addition, the GR_{50} in *O. viciifolia* seedling was over two-fold and six-fold higher than *M. sativa* at the first and second harvests, respectively (Peel *et al.*, 2013). However, no study has addressed the impact of glyphosate application on seed production. Hard seed levels vary considerably in *O. viciifolia* (up to 90%), and it appears to vary considerably with the cultivars (Bhattarai and Biligetu, 2018). Hard seed pod character may increase weediness of glyphosate tolerant *O. viciifolia* as reported for *M. sativa* (USDA, 2005) suggesting that *O. viciifolia* might pose weediness in ecological sensitive areas where it is not native and/or disperse into wild populations and persist in seed banks.

Glyphosate-resistant crops have become a significant part of cropping systems in North America while it remains used extensively in the mediterranean basin probably due to lawsuits and concerns about gene flow and impacts on organic agriculture (Putnam and Orloff, 2013). *Medicago sativa* is a relatively recent crop to have glyphosate-resistant technology introduced. While weed control in sainfoin still a complex issue, *O. viciifolia* has not yet benefited from this technology. Given the low vigour of sainfoin, glyphosate resistant *O. viciifolia* offers new weed control options for sainfoin establishment for an improved long-term crop vigour and yield (McCordick *et al.*, 2008). Adopted this technology could encourage many growers to adopt sainfoin as an alternative forage for apparent improvements in crop safety, quality, profitability and herbicide application simplicity.

Nutritional interest and animal performance

Livestock production is a major and highly diverse component of agriculture that is being exposed to changes in climate impacting on forage and feed crop production (Moore and Ghahramani, 2013; Rojas-Downing *et al.*, 2017; Godde *et al.*, 2021). *O. viciifolia* has aroused renewed interest in its use in livestock diets, as it has important nutritional properties such as high palatability and great nutritional value leading to very satisfactory animal performance (Gayrard *et al.*, 2021). Scharenberg *et al.* (2007*a*) found that the palatability of dried and ensiled *O. viciifolia* was 20–24% higher than that of grasses and 10–29% higher than for *Trifolium pratense* L. and *M. sativa* (Waghorn *et al.*, 1990). *O. viciifolia* hay was preferred to *L. corniculatus* hay by sheep (Scharenberg *et al.*, 2007*b*) and nonlactating cows (Scharenberg *et al.*, 2009; Lagrange *et al.*, 2020). Contrary to forages like alfalfa, sainfoin is a non-bloating legume due to the presence of condensed tannins that attenuate the formation of biofilms in the rumen (Wang *et al.*, 2006). In addition, condensed tannins attenuate the excessive accumulation of ammonia in the rumen through reductions in proteolysis (Lagrange *et al.*, 2020). Finally, sainfoin has been shown to contain high concentrations of non-structural carbohydrates that provide carbon skeletons for an efficient synthesis of microbial protein (Lagrange *et al.*, 2021; Villalba *et al.*, 2021). Collectively, these nutritional benefits contribute to explain the high preference for this forage displayed by ruminants. Mammalian herbivores base their dietary preferences on the association between the orosensorial properties of forages and their post-ingestive consequences (Provenza, 1995) and animals form strong preferences for forages that supply carbohydrates and nitrogen in amounts and proportions that satisfy their daily requirements (Villalba and Provenza, 2000). In contrast, herbivores avoid feeds that enhance rumen distension such as those that induce bloat (Villalba *et al.*, 2009), as well as those forages that yield high concentrations of rumen ammonia (Villalba and Provenza, 1997).

Onobrychis viciifolia can be grown as a monoculture or in mixtures with perennial grasses and *M. sativa* (Moyer, 1985; Goplen *et al.*, 1991; Frame *et al.*, 1998; Carbonero *et al.*, 2011). In recent years, the grazing of *O. viciifolia* as a monoculture, mixed with perennial grasses (*Festuca pratensis* Hudds. and *P. pratense*) or mixed with *M. sativa* has become a widespread practice in several regions of the world (Frame *et al.*, 1998; Carbonero *et al.*, 2011; Biligetu *et al.*, 2021). *Onobrychis viciifolia*-grasses mixtures generally have higher yields and quality than grasses and *O. viciifolia* in monoculture. Liu *et al.* (2006) reported a forage yield of 9.1 t/ha of dry matter for a mixture of *O. viciifolia*-*F. pratensis* seeded in a ratio of 2:1 compared to the monoculture of *O. viciifolia* which gave 7.5 t/ha of dry matter. *Onobrychis viciifolia* can be used primarily as hay or grazed directly, but it can also be cut for silage (Bland, 1971; Sheldrick *et al.*, 1987; Waghorn *et al.*, 1998).

The daily gain reported in heifers was 0.96 and 0.91 kg with *O. viciifolia* and *M. sativa*-grass hay, respectively (Parker and Moss, 1981), and 0.80 and 0.67 kg for heifers on *O. viciifolia* and *M. sativa* pastures, respectively (Marten *et al.*, 1987). Thus, *O. viciifolia* has been reported as an excellent pasture plant (Bonciarelli and Coravelli, 1963; Ferret, 1975; Bencivenga and Negri, 1983). When *O. viciifolia* was grazed as a sole diet, cows, and lambs liveweight gain was similar to *T. repens* and about 20% greater than for *M. sativa* (Waghorn, 2008). Weight gains in beef cattle would be equivalent for *O. viciifolia* hay and that of *M. sativa* (Jensen *et al.*, 1968), and in the case of pasture, the weight gains were higher for *O. viciifolia* compared to *M. sativa* (Hanna and Smoliak, 1968), explained by the lower incidence of bloat and higher efficiency of nitrogen retention due to the presence of tannins in the former (Lagrange *et al.*, 2020). Despite lower concentrate supplementation for grazing rabbits, *O. viciifolia* grassland yielded the highest daily mean growth rates (29 g/day) when compared to natural (26 g/day) and to a pure stand of *Festuca arundinacea* Schreber. (19.2 g/day). Thus, it seems possible to reduce complete feed supplementation without reducing animal performance (Martin *et al.*, 2016; Legendre *et al.*, 2019). To achieve daily mean growth rates of 20 g/day, a grazing area of 0.4 m^2/rabbit is sufficient when *O. viciifolia* is grazed while it should be increased to 0.65 m^2/rabbit when grass and forbs are grazed (Legendre *et al.*, 2019).

Reducing greenhouse gas emissions from livestock

The livestock sector plays an important role in climate change as it accounts for 15% of human-induced greenhouse gases emissions (Hur *et al.*, 2024). Methane represents the second largest anthropogenic greenhouse-effect gas after carbon dioxide (CO_2) (IPCC, 2021). Livestock, enteric fermentations or effluents, contributes about 1/3 of the global methane emissions (Saunois *et al.*, 2020). From an environmental point of view, feeding ruminants with forage containing condensed tannins may offer potential benefits. Nitrogen balance studies performed on sheep fed with conserved *O. viciifolia* have shown a reduction in excretion of urinary N, whereas the opposite pattern was observed with *M. sativa* (Aufrere *et al.*, 2008; Theodoridou *et al.*, 2010). Urinary N can pollute water resources through excessive nitrate levels (Hoste and Niderkorn, 2019) and is quickly converted to nitrogen oxide, a greenhouse gas 298 times more potent than carbon dioxide (Vallero, 2019). Moreover, sheep fed *O. viciifolia* increased faecal N excretion, which contributes to organic matter accumulation more than urinary N (Aufrere *et al.*, 2008; Theodoridou *et al.*, 2010), reducing N loses to the atmosphere. Condensed tannins contribute to shift the proportion of excreted N from urine to faeces (Stewart *et al.*, 2019; Lagrange *et al.*, 2020), given the capacity of tannins to bind proteins in the acidic rumen environment and release proteins at greater pH in the intestines for digestion and absorption (Mueller-Harvey *et al.*, 2019). Enteric methane emissions, another greenhouse gas, were reduced in ruminants consuming *O. viciifolia* (Hatew *et al.*, 2015, 2016; Petrič *et al.*, 2022). This reduction depends on the phenological stage and the chemical composition of the biomass. *In vitro*, methane production in *O. viciifolia* hays showed a tendency to increase with the advancement of phenological stage. The best period to cut *O. viciifolia* for hay making was between early and late flowering, when the forage offers high organic matter digestibility, low methane production and more efficient microbial fermentation (Guglielmelli *et al.*, 2011). At flowering stage, *in vitro* gas and methane productions were cultivar dependant (Kaplan, 2011; Ülger and Kaplan, 2016). Hatew *et al.* (2015) suggested that conserved *O. viciifolia* accessions collected worldwide exhibited substantial variation in terms of their effects on rumen *in vitro* methane production, revealing some promising accessions for future investigations. Additionally, the methane yield depended on the chemical composition of the biomass (Amaleviciute-Volunge *et al.*, 2020). The results obtained in metabolic cages indicated that the inclusion of *O. viciifolia* in silage reduces the digestibility of organic matter *in vivo* on castrated male sheep compared to pure timothy (*Phleum pratense* L.), and methane emissions were proportionately lower (Niderkorn *et al.*, 2016). A trial on dairy cows, including 50% *O. viciifolia* silage in a ration of grass silage, resulted in a reduction of 6.0% methane emissions per kg of dry matter ingested. Silage of *O. viciifolia* allowed improved milk in quantity and quality (Huyen *et al.*, 2016*a*, 2016*b*). The consumption of *O. viciifolia* pellets by gastrointestinal nematode-infected lambs decreased methane emission by affecting ruminal methanogens without undesirable changes in the ruminal microbiome or animals' health (Petrič *et al.*, 2022). Adding *O. viciifolia* into *M. sativa* prior to ensiling suppressed silage proteolysis and mitigated rumen CH_4 in a proportion-dependent manner, with a minor negative effect on dry matter digestibility (Rufino-Moya *et al.*, 2019). Therefore, co-ensiling of *M. sativa* with *O. viciifolia* could be used as a promising strategy not only to produce high-quality legume silage but also to reduce N excretion and mitigate rumen CH_4 (Wang *et al.*, 2022). Lower values of CH_4 per kg intake were recorded with *O. viciifolia* silage compared to pure *Phleum pratense* L. silage (Niderkorn *et al.*, 2019). Similar effects were observed *in vitro* when *O. viciifolia* was mixed with *Lolium perenne* L. or *Dactylis glomerata* L. (Niderkorn *et al.*, 2011, 2012) and *in vivo* when *O. viciifolia* was included in diets of dairy cows (Huyen *et al.*, 2016*a*). The significant reduction of total digestive tract neutral detergent fibre digestibility in the presence of *O. viciifolia* compared to pure *P. pratense* was likely the main driver for the reduction of CH_4 emissions. In addition, the acetate:propionate ratio in the rumen, which is strongly related to the availability of hydrogen as a substrate for methanogenic archaea to form CH_4, was lower for *P. pratense*-*O. viciifolia* and *Trifolium pratense*-*O. viciifolia* than for pure *P. pratense*, highlighting the potential of *O. viciifolia* silage to decrease CH_4 emissions via a modification of the fermentative microbial ecosystem in the rumen (Warner *et al.*, 2017). In addition, the reduction of NH_3 emissions and urea in milk were more pronounced than the reduction in methane emissions (McMahon *et al.*, 1999; Guglielmelli *et al.*, 2011; Niderkorn *et al.*, 2011; Williams *et al.*, 2011; Theodoridou *et al.*, 2011; Chung *et al.*, 2013; Copani *et al.*, 2015).

Nutritive value of sainfoin

The nutritional value of *O. viciifolia* is determined by variety, growth stage and growing environment. Several studies have quantified the nutritional values, mainly the concentrations of crude protein, neutral detergent fibre and acidic detergent fibre, of *O. viciifolia* at different stages of growth. After 42 days of regrowth, the nutritive value of *O. viciifolia* was comparable to the first growth vegetative stage, with crude protein ranging between 148–186 g/kg, and neutral detergent fibre and acid detergent fibre concentration ranging 365–454 g/kg and 337–397 g/kg, respectively (Table 2).

Freshly harvested forage, silage and hay of *O. viciifolia* have similar quality and nutritive value (Table 3). The tannins in *O. viciifolia* silage can reduce the proteolysis that takes place in the silo (Wilkins and Jones, 2000). Incorporation of *O. viciifolia* into *M. sativa* forage improves fermentation in laboratory silos. Optimal ruminal fermentation with silage was obtained with a proportion of 60/40 for *M. sativa* and *O. viciifolia*, respectively (Wang *et al.*, 2007). The inclusion of *O. viciifolia* in grass silage has been shown to improve forage quality, fermentation as well as protein protection against microbial and enzymatic degradation (Lee *et al.*, 2008; Lorenz *et al.*, 2010; Copani *et al.*, 2014). *Onobrychis viciifolia* can be offered as dehydrated granules (Gaudin, 2017), but the necessary technological treatments, high temperature and high pressure, can cause a possible destruction of the tannins and a conversion of the tannins from the free majority form to the bound form attached to proteins (Terrill *et al.*, 1992, 2007; Minnee *et al.*, 2002; Lorenz, 2011).

Onobrychis viciifolia was found to increase by 17% the proportion of omega-3 polyunsaturated fatty acid and unsaturated fatty acids in milk and cheese fat from lactating cattle (Girard *et al.*, 2015, 2016), due to condensed tannins modulating the activity of bacteria involved in the processes of biohydrogenation (Vasta *et al.*, 2010; Buccioni *et al.*, 2015). In addition, it has been reported that condensed tannins of *O. viciifolia* reduced protein degradation in the rumen leading to reductions in rumen ammonia concentrations and N losses in urine (Scharenberg *et al.*, 2007*b*). Condensed tannins also increased the plasma concentration of essential amino acids, indicating that the protein escaped from the rumen is digested in the intestine leading to faster animal growth rates and increased milk production (Waghorn *et al.*, 1990; Waghorn, 2008; Girard *et al.*, 2016).

Nutritional benefits

Onobrychis viciifolia is particularly valued for its content of condensed tannins, which have been shown to improve animal health by reducing bloat (McMahon *et al.*, 1999; Sottie, 2014; Wang *et al.*, 2015), and by diminishing gastro-intestinal parasites (Hoste *et al.*, 2015; Desrues *et al.*, 2017). In fact, the intake of *O. viciifolia* fresh leaves (10–20% of the dry matter of *M. sativa*) reduces bloat in cattle by 27% (McMahon *et al.*, 1999) compared to those consuming 100% *M. sativa*. Consequently, *O. viciifolia* could be grazed, offered in as hay or silage *ad libitum*. When *O. viciifolia* is grown in a mixture with *M. sativa*, it has been shown to reduce bloat incidence in beef cattle relative to the grazing of pure *M. sativa* (Sottie, 2014; Malisch *et al.*, 2015). Condensed tannins of *O. viciifolia* hay has shown reduced egg per gram of faeces, and female fertility of parasitic nematodes when fed to livestock (Azuhnwi *et al.*, 2013; Arroyo-Lopez *et al.*, 2014). Anti-parasitic properties of *O. viciifolia* tannins have been demonstrated by both *in vitro* (Barrau *et al.*, 2005) and *in vivo* studies (Molan *et al.*, 2000*a*, 2000*b*, 2002; Hoste *et al.*, 2015). Moreover, sheep increase their intake of *O. viciifolia* through time when parasitized (Gaudin *et al.*, 2019) and show

Table 2. Nutritional value of *Onobrychis viciifolia* at different stages of growth

Growth stage	Variety	Crude protein (g/kg DM)	Neutral detergent fibre (g/kg DM)	Acid detergent fibre (g/kg DM)	References
Vegetative	Anatolian	195–198	378–461	286–334	Bal *et al.* (2006)
	nd				Turk *et al.* (2011)
Flowering	Eski	116–143	372 457	368–392	Parker and Moss (1981)
	nd	121	478	433	Khalilvandi-Behroozyar *et al.* (2010)
	nd	114–177	433–476	343–433	Kaplan (2011)
	Anatolian	145	493	372	Bal *et al.* (2006)
	Nova	125–161	–	313–371	McMahon *et al.* (1999)
	38 accessions	134–175	356–458	351–416	Bhattarai and Biligetu (2018)
Grain filling	Anatolian	130	557	402	Bal *et al.* (2006)
	nd	171	446	338	Turk *et al.* (2011)
Regrowth (42 Days)	Moiry	148–186	365–454	337–397	Azuhnwi *et al.* (2012)
	Sarzens				
	Premier				
	Visnovsky				
	Perly				

Table 3. Characteristics and nutritive value of *Onobrychis viciifolia* feeding forms

	Variety	Dry matter (g/kg)	Organic matter	Crude protein (g/kg DM)	Neutral detergent fibre (g/kg DM)	Acid detergent fibre (g/kg DM)	Condensed tannins (g/kg DM)	Metabolizable energy (%)	References
Fresh	nd	298	927	198	231	202	43.7	9.8	Scharenberg *et al.* (2007*a*)
Hay		968	897	220	239	210	46.2	9.7	
Silage		315	921	211	229	228	28.8	9.1	
Fresh	Perly	–	–	143	415	314	6.2	–	Theodoridou *et al.* (2010)
Frais		–	–	187	355	279	13.6	–	
Hay	nd	–	923	219	391	256	–	–	Guglielmelli *et al.* (2011)
Hay		–	933	207	433	346	–	–	
Hay		–	935	175	441	296	–	–	
Hay		–	942	122	514	409	–	–	
Hay	Zeus	–	924	157	346	249	9.8	–	Niderkorn *et al.* (2012)
Fresh	Reznos	–	–	194	392	258	–	–	Rufino-Moya *et al.* (2022)
Hay		–	–	169	470	340	–	–	
Silage		–	–	169	456	332	–	–	
Pellets	nd	918	–	121	460	357	–	–	Petrič *et al.* (2022)

high preferences for the legume despite the high availability of alternative legumes without tannins like cicer milkvetch (Villalba *et al.*, 2013).

Onobrychis viciifolia has an antiparasitic effect on the most important sheep nematodes (Ríos-De Álvarez *et al.*, 2008; Komáromyová *et al.*, 2021; Petrič *et al.*, 2022). Similar results were obtained with goats (Paolini *et al.*, 2005). While goats are more willing than sheep to consume tanniferous feeds, the potential for self-medication has been demonstrated in both species concerning *H. contortus* (Gaudin *et al.*, 2019). Regular feeding on *O. viciifolia* pastures by small ruminants could therefore be used to improve host resilience and thus reduce pasture contamination. The anthelmintic bioactivity of *O. viciifolia* is maintained in hay or silage (Ojeda-Robertos *et al.*, 2010). Berard *et al.* (2009) proved that *O. viciifolia* silage and hay reduced the excretion of *Escherichia coli* by cattle. The consumption of *O. viciifolia* by small ruminants has also been associated with effects on coccidia (Saratsis *et al.*, 2012) and on infestations by gastrointestinal nematodes (Hoste *et al.*, 2015). These findings contribute to the further development of sustainable grass–legume systems, as evidence for the successful cultivation of *O. viciifolia* as an alternative legume species (Malisch *et al.*, 2017).

Medicinal and pharmacological properties

Global environmental degradation and climate change threaten the foundation of human health and well-being (Pathak and McKinney, 2021; Rocha *et al.*, 2022). Several diseases are all likely to become more common (Faergeman, 2007). Ethnobotanical evidence supports the use of *O. viciifolia* in traditional medicine (Martini, 1981; Mbaveng *et al.*, 2014) (Table 4). Cornara *et al.* (2016) recently reviewed temperate forage legumes as a resource for nutraceuticals and pharmaceuticals. The nutraceutical activity of *O. viciifolia* is due to the presence of a large phenolic complex, dominated by arbutin, rutin, catechin, kaempferol, quercetin, afzelin and condensed tannins (Marais *et al.*, 2000; Regos *et al.*, 2009). These phenolic metabolites are reported as antioxidants, detoxifying agents, reducing blood pressure and anti-cancer agents (Dai and Mumper, 2010).

Establishment characteristics

Climate change is predicted to causes significant changes in composition, establishment, growth and development of pastures and fodder crops (Sunil *et al.*, 2020; Martins-Noguerol *et al.*, 2023). Ease of stand establishment is considered an important trait in perennial forage utilization under climate change. *Onobrychis*

Table 4. Biological activity of *Onobrychis viciifolia*

Plant part	Biological activity	Target/	Reference
Stems and leaves	Anthelmintic properties Antimicrobial activity	*Teladorsagia circumcincta*, *Haemonchus contortus* and *Trichostrongylus colubriformis*	Paolini *et al.* (2004)
		Escherichia coli O157:H7	Barrau *et al.* (2005)
		Escherichia coli	Liu *et al.* (2013)
Dried and pulverized roots	Antiseptic and vulnerary	Placed directly on the wounds	Martini (1981)

viciifolia establishment depends on soil characteristics, seeding (size, colour of tegument, milled *vs* unmilled) and weed competition. *Onobrychis viciifolia* seeds germinate rapidly and are easy to establish in the Brown, Dark Brown and Black soil zones of western Canada, as well as stony clay loam soils in UK (Goplen *et al*., 1991; Carbonero *et al*., 2011).

The areal expansion of semiarid and subhumid zones under climate change will increase at the expense of the contraction of arid and humid zones (Li *et al*., 2021*a*, 2021*b*). *Onobrychis viciifolia* performs well over multitude of climatic areas. In the warm Mediterranean Basin, *O. viciifolia* is normally drilled either in early autumn or at the beginning of spring. Conversely, in colder areas like the UK, it is recommended to drill *O. viciifolia* between April and July (Jensen *et al*., 1968; Goplen *et al*., 1991). Early sowing can improve the development of the plants due to the early development of roots (Nikola, 1998). Global warming due to climate change will expose plants and their seeds to novel climatic conditions and likely affect seed germination responses (Gremer *et al*., 2020; Mondoni *et al*., 2022). Species with a wide range of temperature for germination could have a better adaptability to climate change (Bandara *et al*., 2019). Although there is limited information available on its seed germination, *O. viciifolia* has a wide range of optimum temperature for germination, but it is normally advised to drill it between 10–27°C and never below 5°C (Carleton *et al*., 1968; Jensen *et al*., 1968; Smoliak *et al*., 1972). There are conflicting views on the relative germination of milled and unmilled *O. viciifolia* seeds. Wiesner *et al.* (1968) reported a higher germination percentage for milled seeds, but no significant difference in germination among the two types was observed by Chen (1992). Noorbakhshian *et al.* (2011) found improved germination and seedling vigour for *O. viciifolia* after removing the seed pods. Use of de-hulled seeds could provide staggered germination and thus cushion potential weather disturbances (Wiesner *et al*., 1968; Chen, 1992; Demdoum, 2012). To enhance *O. viciifolia* germination and early establishment, several studies report the need for seed pod removal rather than seed scarification (Bhattarai and Biligetu, 2018). In addition, seedlings emerging from seeds with intact pod may have a high probability of fungal infestation (*Alternaria* and *Fusarium* spp.). Slow and non-uniform seedling growth and high weed infestations may be other limiting factors for sowing seeds with pods (Noorbakhshian *et al*., 2011).

Variation among *O. viciifolia* germplasm for seed size, seed weight and seed coat colour would enhance the species adoption by farmers under climate change. The germination percentage was higher for brown than green seeds as the former are physiologically mature (Thomson, 1938; Noorbakhshian *et al*., 2011). Brown seeds colouration has important functions in plants including a role in camouflage and thermoregulation, and protection against UV-radiation and pathogens (Roulin, 2014). Germination is also affected by seed size, which varies among *O. viciifolia* cultivars. Bhattarai and Biligetu (2018) found that final germination was increased by seed pod removal but not with seed size. In *O. viciifolia*, the medium seed size class (1000-seed weight of 21 g) and the large seed size class (1000-seed weight of 28 g) had a final germination of 90%–93% at temperature of 25°C, but the small seed class (1000-seed weight of 12 g) had a final germination lower than 10% due to high degree of physical dormancy (Bhattarai and Biligetu, 2018). Cash and Ditterline (1996) reported that *O. viciifolia* seedlings emerged more rapidly from large seeds. The use of large fully mature seeds increases establishment success giving stronger plants, with more nodules and high rates of N_2 fixation (Cash and Ditterline, 1996). The seeding density of *O. viciifolia* depends upon seed size, soil type, soil moisture, purpose and method of seeding. There is almost no data available to confirm the effect of *O. viciifolia* seeding density on stand establishment, forage yield and other agronomic performance. To establish a population of 70–150 adult plants/m^2 in the first year, authors recommend seed densities of 40–50 kg/ha of de-hulled seeds (or 80–120 kg/ha hulled seeds) (Sheldrick *et al*., 1987; Frame *et al*., 1998) at a depth of 1–2 cm in Canada (Hill, 1997). Conversely, in China, a depth of 4–5 cm was recommended (Chen, 1992). The recommended row spacing is between 50–60 cm for a better stand establishment (Goplen *et al*., 1991; Stevovic *et al*., 2010).

It is recognized that weed pressure associated with climate change is a significant threat to crop production, either through increased temperatures, rainfall shift and elevated CO_2 levels, but the current knowledge of these effects is very sparse (Ramesh *et al*., 2017; Munda *et al*., 2024). *Onobrychis viciifolia* is a non-aggressive crop during seedling establishment. Thus, weed control in the first year is important for good establishment and high forage production in subsequent years. In the first year of establishment, Moyer (1985) found weeds made up 98% of dry matter yield in *O. viciifolia* fields without any weed control measures Lethbridge (Canada). Koivisto and Lane (2001) suggested using a non-competitive grass as a companion crop to aid in weed control in the establishment year. Chemical weed control in pure stands of *O. viciifolia* resulted in higher seed yield than stands with *H. vulgare* as a companion crop in Europe (Dimitrova, 2010).

Recent advances

Climate change has a substantial bearing on crop productivity and food security, and hence there is a need to develop resilience to mitigate climate change induced impacts in crop plants (Acevedo *et al*., 2020; FAO, 2020; Raj *et al*., 2022). The challenge is to try to preserve the resilience of our ecosystems in the years to come, and to maintain food security by protecting important crop species and finding ways to increase their productivity. Despite *O. viciifolia* potential to tackle climate change adverse effects, the species is relatively understudied, and several aspects need to be addressed. In recent years, 'HealthyHay' (http://legumeplus.eu/healthyhay-project) and 'LegumePlus' (http://legumeplus.eu) projects conducted genetic analyses, agronomic, biological and chemical evaluations, nutritional analyses, environmental assessments and developed methodologies for screening for genetic improvement of 362 different *O. viciifolia* accessions across Europe. Nevertheless, there is no report of registration of new improved *O. viciifolia* cultivars from these large-scale research projects (Poudel *et al*., 2023). In 2000, a new breeding initiative of *O. viciifolia* focusing on improvement of the compatibility of *O. viciifolia* in *M. sativa* stands to reduce *M. sativa* bloat led to the creation of two new Canadian cultivars, namely AAC-Mountainview and AAC-Glenview released in 2015 and 2018, respectively (Poudel *et al*., 2023). AAC-Mountainview was derived from single-cycle selection under competition with *M. sativa*, whereas AAC-Glenview was selected for persistence in *M. sativa* stands, followed by improved grazing tolerance in a grazing trial. The variation in dry matter yield in both cultivars is low compared to the Romanian cultivar Splendid, but higher than the Kazakhstan cultivar Nova based on recent tests in Lethbridge

(South Ouest Canada) in monocultures. Nevertheless, AAC-Mountainview and AAC-Glenview showed significant advantages over parents when seeded with *M. sativa*. These cultivars are successful, and demand for their seeds is increasing considerably (Poudel *et al.*, 2023).

Overall, climate change has exemplified the need for continued research into crop environmental stress tolerance (Jing *et al.*, 2024). Current updates and recent advances in the physiological, molecular and genetic perspectives of plant responses to environmental stresses may offer insights underlying these responses and how this pool of knowledge can be explored to develop plants for future climates (Kumar *et al.*, 2023). In recent years, there has been a growing focus on research endeavours aimed at enhancing the resilience of *O. viciifolia* to both abiotic and biotic stresses providing opportunity for climate change adaptation and mitigation. To address the challenge of establishing *O. viciifolia* in drought conditions, Irani *et al.* (2015*a*) identified *O. viciifolia* plants that exhibited resilience to drought and displayed high yields. These plants were characterized by elevated foliar proline contents, presenting a potential physiological marker for screening drought tolerance for climate change adaptation and mitigation. Moreover, enhancing the activity of two crucial antioxidant enzymes, glutathione reductase (GR) and ascorbate peroxidase (APX), can lead to successful breeding of *O. viciifolia* with improved drought tolerance (Beyaz, 2019). On the other hand, the growth of *O. viciifolia* is constrained by powdery mildew (*Erysiphe polygoni*), with several tolerant accessions having been previously identified (Jafari *et al.*, 2014; Alizadeh *et al.*, 2021). Li *et al.* (2021*a*, 2021*b*) investigated *O. viciifolia* seed response under saline conditions and offered valuable insights for advancing the establishment and cultivation of salt-tolerant *O. viciifolia* in saline lands in China. The challenges posed by environmental stresses may be influential in the reduced persistence of *O. viciifolia*. Therefore, forthcoming *O. viciifolia* breeding endeavours ought to prioritize the creation of cultivars resilient to both biotic and abiotic stressors.

Progress in enhancing the molecular characteristics of *O. viciifolia* has significantly trailed behind that of other forage legume species, primarily because of the limited genomic resources. While several genetic markers have been established for *O. viciifolia* (Kempf, 2016; Mora-Ortiz *et al.*, 2016; Shen *et al.*, 2019), and a complete chloroplast genome sequence has been recently disclosed (Jin *et al.*, 2021), there is currently no existing reference nuclear genome sequence for this species. Progress in molecular improvement has been advancing in recent years, with the accumulation of transcriptomic data from various tissues across a limited number of genotypes (Kempf, 2016; Mora-Ortiz *et al.*, 2016; Shen *et al.*, 2019; Yin *et al.*, 2020; Jin *et al.*, 2021; Qiao *et al.*, 2021). Additionally, there has been an evaluation of microRNAs (miRNAs) in *O. viciifolia* cultivated at different altitudes (Yin *et al.*, 2020). Considering the growing interest in *O. viciifolia*, further advancements should continue to unfold in this sphere in the years ahead, contributing to the facilitation of breeding activities. Alongside the existing limited supply of genetic data for tetraploid *O. viciifolia*, there exists a notable lack of accessible biotechnological tools. This shortfall has impeded both functional genetic investigations and progress in advanced molecular breeding initiatives. There has been some advancement in this domain with the introduction of a transient virus-induced gene silencing method in *O. viciifolia*. This method has proven successful in downregulating the expression of the phytoene desaturase gene, signifying recent progress in the field.

Future perspectives

In the present review, *O. viciifolia* appears as a plant with high application potential with agronomic, ecological and economic interest in the present scenario of climate change. Advances in recent years have provided more opportunities for *O. viciifolia* to be considered as an alternative for farmers, particularly those interested in producing locally sourced protein and sustainable agricultural practices (Sheppard *et al.*, 2019). Although the agronomical and ecological potential of *O. viciifolia* have recently received due attention, its general biological and physiological attributes have not been well-investigated. Evaluating these basic facets may extend its cultivation and pave the way for novel applications in the present context of climate change (Sakhraoui *et al.*, 2023). In this sense, research efforts on the ecology, stress tolerance and uses of *O. viciifolia* should be increased. Thus, use of both genetic manipulation and traditional breeding approaches will be required to develop salt-tolerant cultivars better able to cope with high salinities in marginal agriculture areas affected by salinization in the present climate change scenario.

In view of our review, there are mainly five deficiencies in the research on *O. viciifolia* and its relationship with climate change: (1) Most of the studies on *O. viciifolia* ecophysiology have been focused on seedlings, while research concerning adult plants is scarce. Plant physiological characteristics often show differences in different growth stages, so the seedling stage may not represent the physiological characteristics of the whole plant life cycle (Mganga *et al.*, 2019). Therefore, the research on physiological responses to environmental stressors related to climate change should be carried out for different growth stages of *O. viciifolia*, especially adult plants. (2) The studies on stress tolerance of *O. viciifolia* have been mainly focused on salt and drought tolerance, while the research on the responses to other environmental stressors, such as extremes of air temperatures, are scarce or non-existent. Therefore, more research is needed on the responses of *O. viciifolia* to different environmental stressors related to climate change, besides salinity and drought, and on the interactive effects of the combination of different environmental stresses. (3) The study of stress tolerance mechanism has been mainly focused on the observation of physiological changes, while the research on anatomical, morphological and genetic adaptation mechanisms is scarce. To further clarify the stress resistance of *O. viciifolia* to stressors related to climate change, anatomical, morphological and genetic studies should be conducted. Covering these knowledge gaps and their incorporation in hybridization and breeding programs can be useful in creating new cultivars of *O. viciifolia* better adapted to climate change. (4) *Onobrychis viciifolia* is relatively resistant to biotic stresses compared to other forage legume species and appears to rely on cultivar choices and thus represent a potential source for breeding (Carbonero *et al.*, 2011). This resistance will need to be confirmed by further rigorous field pathology studies to determine the susceptibility of selected lines, and the potential resistance mechanism should be studied to see if it is possible to transfer this into new cultivars. (5) The evaluations of ecological and economic benefits and impact of *O. viciifolia* production are mostly qualitative, lacking quantitative evaluations. This may limit farmers and the decision-making departments of public administrations to pay attention to its application values. Therefore, quantitative analysis should be carried out in the evaluation of ecological and economic benefits of *O. viciifolia*. (6) There is a lack of long-term observation experiments after sowing pastures with *O. viciifolia* or using this legume in ecological restoration projects. This sort of long-term studies would be a great opportunity to improve our knowledge on the benefits of *O. viciifolia* as a biological tool to mitigate and adapt to climate change. (7) The genomes of *O. viciifolia* have not yet been fully sequenced, and a limited number of genetic markers are present, except for some transcriptomics data to apply in crop improvement studies and functional genomics (Kempf, 2016; Mora-Ortiz *et al*., 2016; He *et al*., 2024). In fact, recent breeding studies on *O. viciifolia* have led to improvements in this crop as bloat-free forage legume by enhancing its yield, biomass productivity, grazing tolerance and fatty acid composition (Subedi, 2018; Wijekoon *et al*., 2021). However, only a few *O. viciifolia* cultivars are available and new cultivars with high dry matter yield and persistence under regional growing conditions are required (Bhattarai *et al*., 2016; Sheppard *et al*., 2019). Further breeding studies are necessary on the improvements in weed control, establishment, seed dormancy and genetic characterisation to enable effective pre-breeding programmes in different environments.

Conclusions

Onobrychis viciifolia is a forage legume of renewed interest worldwide, with equally weighted advantages and disadvantages that prevent many farmers from considering this crop a viable alternative to other forage legumes. However, advances in recent years have provided more opportunities for sainfoin to be considered as an alternative choice for farmers, particularly for its agronomical and ecological interests, nutritional benefits and nutraceutical proprieties. However, some knowledge gaps and application should be studied deeply to promote *O. viciifolia* use for climate change adaptation and mitigation. In this sense, research is required to select and breed potentially useful varieties combining nutritional, agronomic and environmental potential.

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References

Abou-El-Enain MM (2002) Chromosomal criteria and their phylogenetic implications in the genus *Onobrychis* Mill. sect. *Lophobrychis* (*Leguminosae*), with special reference to Egyptian species. *Botanical Journal of the Linnean Society* **139**, 409–414. https://doi.org/10.1046/j.1095-8339.2002.00075.x

Acevedo M, Pixley K, Zinyengere N, Meng S, Tufan H, Cichy K, Bizikova L, Isaacs K, Ghezzi-Kopel K and Porciello J (2020) A scoping review of adoption of climate-resilient crops by small-scale producers in low- and middle-income countries. *Nature Plants* **6**, 1231–1241. https://doi.org/10.1038/s41477-020-00783-z

Adamczyk B, Karonen M, Adamczyk S, Engström MT, Laakso T, Saranpää P, Kitunen V, Smolander A and Simon J (2017) Tannins can slow-down but also speed-up soil enzymatic activity in boreal forest. *Soil Biology and Biochemistry* **107**, 60–67. https://doi.org/10.1016/j.soilbio.2016.12.027

Adamczyk B, Sietiö O-M, Biasi C and Heinonsalo J (2019) Interaction between tannins and fungal necro mass stabilizes fungal residues in boreal forest soils. *New Phytologist* **223**, 16–21. https://doi.org/10.1111/nph.15729

Adjesiwor AT and Islam MA (2016) Rising nitrogen fertilizer prices and projected increase in maize ethanol production: the future of forage production and the potential of legumes in forage production systems. *Grassland Science* **62**, 203–212. https://doi.org/10.1111/grs.12130

Akram NA, Shafiq F and Ashraf M (2018) Peanut (*Arachis hypogaea L.*): a prospective legume crop to offer multiple health benefits under changing climate. *Comprehensive Reviews in Food Science and Food Safety* **17**, 1325–1338. https://doi.org/10.1111/1541-4337.12383

Alizadeh MA, Jafari AA, Sepahvand K, Davazdahemami S, Moeini MR, Normand Moaied F and Naseri B (2021) Evaluation of sainfoin accessions exposed to powdery mildew disease at four locations in Iran. *Tropical Grasslands-Forrajes Tropicales* **9**, 97–108. https://doi.org/10.17138/tgft(9)97-108

Al-Turki TA, Davy AJ, Al-Ammari BS and Basahi MA (2022) Seed germination characteristics of some medicinally important desert plants from the Arabian Peninsula. *Journal of Arid Environments* **198**, 104689. https://doi.org/10.1016/j.jaridenv.2021.104689

Amaleviciute-Volunge K, Slepetiene A and Butkute B (2020) Methane yield of perennial grasses as affected by the chemical composition of their biomass. *Zemdirbyste-Agriculture* **107**, 243–248. https://doi.org/10.13080/z-a.2020.107.031

Amirahmadi A, Kazempour-Osaloo S, Moein F, Kaveh A and Maassoumi AA (2014) Molecular systematics of the tribe Hedysareae (Fabaceae) based on nrDNA ITS and plastid trnL-F and matK sequences. *Plant Systematics and Evolution* **300**, 729–747. https://doi.org/10.1007/s00606-013-0916-5

Anderson C (2016) Alternative forage. Sainfoin, fenugreek: Not your everyday feed. Available at https://www.dtnpf.com/agriculture/web/ag/news/article/2016/03/23/sainfoin-fenugreekeveryday-feed

Angevain M and Prosperi JM (1995) Les Sainfoins ou le Genre *Onobrychis*. In Prosperi JM, Guy el P and Balfourier F (eds), *Ressources Génétiques des Plantes Fourragères et â Gazon*. Paris: BRG/INRA, pp. 169–175.

Arroyo-Lopez C, Manolaraki F, Saratsis A, Saratsi K, Stefanakis A, Skampardonis V, Voutzourakis N, Hoste H and Sotiraki S (2014) Anthelmintic effect of carob pods and sainfoin hay when fed to lambs after experimental trickle infections with *Haemonchus contortus* and *Trichostrongylus colubriformis*. *Parasite*, **21**, 21–71. https://doi.org/10.1051%2Fparasite%2F2014074

Asci OO (2011) Salt tolerance in red clover (*Trifolium pratense* L.) seedlings. *African Journal of Biotechnology* **10**, 8774–8781. https://doi.org/10.5897/AJB11.596

Aufrere J, Dudilieu M and Poncet C (2008) *In vivo* and *in situ* measurements of the digestive characteristics of sainfoin in comparison with Lucerne fed to sheep as fresh forages at two growth stages and as hay. *Animal* **2**, 1331–1339. https://doi.org/10.1017/s1751731108002450

Avci S and Kaya MD (2013) Seed and germination characteristics of wild *Onobrychis* taxa in Turkey. *Turk Tarim ve Ormancilik Dergisi/Turkish Journal of Agriculture and Forestry* **37**, 555–560. https://doi.org/10.3906/tar-1211-29

Avci S, Ilhan E, Erayman M and Sancak C (2014) Analysis of *Onobrychis* genetic diversity using SSR markers from related legume species. *Journal of Animal and Plant Sciences* **24**, 556–566.

Ayers GS (1993) Return of information about sainfoin. *American Bee Journal* **133**, 257–259.

Azuhnwi BN, Thomann B, Arrigo Y, Boller B, Hess HD, Kreuzer M and Dohme-Meier F (2012) Ruminal dry matter and crude protein degradation kinetics of five sainfoin (*Onobrychis viciifolia* Scop.) accessions differing in condensed tannin content and obtained from different harvests. *Animal*

Feed Science and Technology **177**, 135–143. https://doi.org/10.1016/j.anifeedsci.2012.08.004

Azuhnwi BN, Hertzberg H, Arrigo Y, Gutzwiller A, Hess HD, Mueller-Harvey I, Torgerson P, Kreuzer M and Dohme-Meier F (2013) Investigation of sainfoin (*Onobrychis viciifolia*) cultivar differences on nitrogen balance and fecal egg count in artificially infected lambs. *Journal of Animal Science* **91**, 2342–2354. https://doi.org/10.2527/jas.2012-5351

Baimiev AK, Baimiev AK, Gubaidullin II, Kulikova OL and Chemeris AV (2007) Bacteria closely related to *Phyllobacterium trifolii* according to their 16S rRNA gene are discovered in the nodules of Hungarian sainfoin. *Russian Journal of Genetics* **43**, 587–590. https://doi.org/10.1134/S1022795407050146

Bajwa AA, Farooq M, Al-Sadi AM, Nawaz A, Jabran K and Siddique KHM (2020) Impact of climate change on biology and management of wheat pests. *Crop Protection* **137**, 105304. https://doi.org/10.1016/j.cropro.2020.105304

Bakala HS, Mandahal S, Sarao LK and Srivastava P (2021) Breeding wheat for biotic stress resistance: achievements, challenges and prospects. In Mahmood-ur-Rahman Ansari (Ed.), *Current Trends Wheat Research* (Chap. 2). London, UK: IntechOpen. https://doi.org/10.5772/intechopen.97359

Bal MA, Ozturk D, Aydin R, Erol A, Ozkan CO, Ata M, Karakas E and Karabay P (2006) Nutritive value of sainfoin (*Onobrychis viciaefolia*) harvested at different maturity stages. *Pakistan Journal of Biological Sciences* **9**, 205–209. http://doi.org/10.3923/pjbs.2006.205.209

Bandara RG, Finch J, Walck JL, Hidayati SN and Havens K (2019) Germination niche breadth and potential response to climate change differ among three North American perennials. *Folia Geobotanica* **54**, 5–17. https://doi.org/10.1007/s12224-019-09347-2

Barrau E, Fabre N, Fouraste I and Hoste H (2005) Effect of bioactive compounds from Sainfoin (*Onobrychis viciifolia* Scop.) on the *in vitro* larval migration of *Haemonchus contortus*: role of tannins and flavonol glycosides. *Parasitology* **131**, 531–538. https://doi.org/10.1017/s0031182005008024

Beaumont NJ, Austen MC, Atkins JP, Burdon D, Degraer S, Dentinho TP, Derous S, Holm P, Horton T, van Eerland E, Marboe AH, Starkey D, Townsend M and Zarzycki T (2007) Identification, definition and quantification of goods and services provided by marine biodiversity: implications for the ecosystem approach. *Marine Pollution Bulletin* **54**, 253–265. https://doi.org/10.1016/j.marpolbul.2006.12.003

Beladi M, Habibi D, Kashani A, Paknejad F and Nooralvandi T (2011) Phytoremediation of lead and copper by sainfoin (*Onobrychis viciifolia*): role of antioxidant enzymes and biochemical biomarkers. *American-Eurasian Journal of Agricultural & Environmental Sciences* **10**, 440–449.

Benaiges C (1971) *La esparceta*. Madrid, España: Ministerio de Agricultura.

Bencivenga M and Negri V (1983) Le leguminose dei pascou umbri. *Revue Agronomie* **2**, 315–326.

Benoit RE and Starkey RL (1968) Enzyme inactivation as a factor in the inhibition of decomposition of organic matter by tannins. *Soil Science* **105**, 203–208. https://doi.org/10.1097/00010694-196804000-00001

Ben-Salem N, Álvarez S and López-Vicente M (2018) Soil and water conservation in rainfed vineyards with common sainfoin and spontaneous vegetation under different ground conditions. *Water* **10**, 1058. https://doi.org/10.3390/w10081058

Berard NC, Holley RA, McAllister TA, Ominski KH, Wittenberg KM, Bouchard KS, Bouchard JJ and Krause DO (2009) Potential to reduce *Escherichia coli* shedding in cattle feces by using sainfoin (*Onobrychis viciifolia*) forage, tested *in vitro* and *in vivo*. *Applied and Environmental Microbiology* **75**, 1074–1079. https://doi.org/10.1128/AEM.00983-08

Beyaz R (2019) Biochemical responses of sainfoin shoot and root tissues to drought stress in *in vitro* culture. *Legume Research* **42**, 173–177. https://doi.org/10.18805/LR-460

Beyaz R and Yildiz M (2021) Influence of peg-induced drought stress on antioxidant components of callus tissue of sainfoin (*Onobrychis viciifolia* Scop.) ecotypes. *Legume Research* **44**, 197–201. https://doi.org/10.18805/LR-556

Beyaz R, Sancak C, Yildiz C, Kuşvuran S and Yildiz M (2016) Physiological responses of the M1 sainfoin (*Onobrychis viciifolia* Scop) plants to gamma radiation. *Applied Radiation and Isotopes* **118**, 73–79. https://doi.org/10.1016/j.apradiso.2016.09.005

Beyaz R, Sancak C and Yildiz M (2018) Morphological and biochemical responses of sainfoin (*Onobrychis viciifolia* Scop.) ecotypes to salinity. *Legume Research* **41**, 253–258. https://doi.org/10.18805/LR-353

Bhattarai S and Biligetu B (2018) Effects of seed size, seed pod removal and temperature on seed germination of *Onobrychis viciifolia*. *Seed Science and Technology* **46**, 113–117. https://doi.org/10.15258/sst.2018.46.1.11

Bhattarai S, Coulman B and Biligetu B (2016) Sainfoin (*Onobrychis viciifolia*): renewed interest as a forage legume for Western Canada. *Canadian Journal of Plant Science* **96**, 748–756. https://doi.org/10.1139/cjps-2015-0378

Bibi F and Rahman A (2023) An overview of climate change impacts on agriculture and their mitigation strategies. *Agriculture* **13**, 1508. https://doi.org/10.3390/agriculture13081508

Biligetu B, Jefferson PG, Lardner HA and Acharya SN (2021) Evaluation of sainfoin (*Onobrychis viciifolia*) for forage yield and persistence in sainfoin–alfalfa (*Medicago sativa*) mixtures and under different harvest frequencies. *Canadian Journal of Plant Science* **101**, 525–535.

Bland BF (1971) *Crop Production: Cereals and Legumes*. London, UK: Academic Press, pp. 431–444.

Bogoyavlenskii SG (1955) Bees and sainfoin. *Pchelovodstvo Mosk* **32**, 10–14.

Bogoyavlenskii SG (1974) The multiplicity of visits to sainfoin by honey bees and its importance for the yields of seeds. *Proceedings of the 3rd International Symposium on Pollination*, pp. 121–127.

Bolat İ (2019) Microbial biomass, basal respiration, and microbial indices of soil in diverse croplands in a region of northwestern Turkey (Bartın). *Environmental Monitoring and Assessment* **191**, 695. https://doi.org/10.1007/s10661-019-7817-1

Bolger TP and Matches AG (1990) Water use efficiency and yield of sainfoin and alfalfa. *Crop Science* **30**, 143–148.

Bonciarelli F and Coravelli G (1963) Primi risultati di prove spenmentalt sul migrioramento dei pascoli dell' appennino umbri. *Ann. Fec. Agr. Un/v. Perugia*. **18**, 203–216.

Böttger JA, Bundy CS, Oesterle N and Hanson SF (2013) Phylogenetic analysis of the alfalfa weevil complex (*Coleoptera*: *Curculionidae*) in North America. *Journal of Economic Entomology* **106**, 426–436. https://doi.org/10.1603/EC12262

Buccioni A, Pauselli M, Viti C, Minieri S, Pallara G, Roscini V, Rapaccini S, Marinucci MT, Lupi P, Conte G and Mele M (2015) Milk fatty acid composition, rumen microbial population, and animal performances in response to diets rich in linoleic acid supplemented with chestnut or quebracho tannins in dairy ewes. *Journal of Dairy Science* **98**, 1145–1156. https://doi.org/10.3168/jds.2014-8651

Bungener P, Balls GR, Nussbaum S, Geissmann M, Grub A and Fuhrer J (1999) Leaf injury characteristics of grassland species exposed to ozone in relation to soil moisture condition and vapour pressure deficit. *New Phytologist* **142**, 271–282. https://doi.org/10.1046/j.1469-8137.1999.00390.x

Burton JC and Curley RL (1968) Nodulation and nitrogen fixation in sainfoin (*Onobrychis sativa* LAM.) as influenced by strains of rhizobia. *Sainfoin Symposium*, pp. 3–5.

Cammarano D, Ceccarelli S, Grando S, Romagosa I, Benbelkacem A, Akar T, Al-Yassin A, Pecchioni N, Francia E and Ronga D (2019) The impact of climate change on barley yield in the Mediterranean basin. *European Journal of Agronomy* **106**, 1–11. https://doi.org/10.1016/j.eja.2019.03.002

Carbonero CH, Mueller-Harvey I, Brown TA and Smith L (2011) Sainfoin (*Onobrychis viciifolia*): a beneficial forage legume. *Plant Genetic Resources* **9**, 70–85. http://doi.org/10.1017/S1479262110000328

Carbonero CH, Carbonero F, Smith LMJ and Brown TA (2013) Cytological characterization of the underutilized forage crop *Onobrychis viciifolia* Scop. and other members of the *Onobrychis* genus. *Genetic Resources and Crop Evolution* **60**, 1987–1996. https://doi.org/10.1007/s10722-013-9967-2

Carleton AE, Cooper CS and Wisner LE (1968) Effect of seed pod and temperature on speed of germination and seedling elongation of sainfoin (*Onobrychis viciaefolia* Scop.). *Agronomy Journal* **60**, 81–84. https://doi.org/10.2134/agronj1968.00021962006000010026x

Cash SD and Ditterline RL (1996) Seed size effects on growth and N-2 fixation of juvenile sainfoin. *Field Crops Research* **46**, 145–151. https://doi.org/10.1016/0378-4290(95)00096-8

Chen B (1992) *Sainfoin*. Lanzhou, China: Gansun Sci-tech Press ed.

Chu L, Gao Y, Chen L, McCullough PE, Jespersen D, Sapkota S, Bagavathiannan M and Yu J (2022) Impact of environmental factors on seed germination and seedling emergence of white clover (*Trifolium repens* L.). *Agronomy* **12**, 190. https://doi.org/10.3390/agronomy12010190

Chung YH, Mc Geough EJ, Acharya S, McAllister TA, McGinn SM, Harstad OM and Beauchemin KA (2013) Enteric methane emission, diet digestibility, and nitrogen excretion from beef heifers fed sainfoin or alfalfa. *Journal of Animal Science* **91**(10), 4861–4874. https://doi.org/10.2527/jas.2013-6498

Cirujeda A, Marí AI, Murillo S, Aibar J, Pardo G and Solé-Senan XO (2019) May the inclusion of a legume crop change weed composition in cereal fields? Example of sainfoin in Aragon (Spain). *Agronomy* **9**, 134. https://doi.org/10.3390/agronomy9030134

Clement SL, Griswold TL, Rus RW, Hellier BC and Stout DM (2006) Bee associates of flowering *Astragalus* and *Onobrychis* genebank accessions at a Snake River site in Eastern Washington. *Journal of the Kansas Entomological Society* **79**, 254–260. https://doi.org/10.2317/0505.02.1

Clemensen AK, Villalba JJ, Rottinghaus GE, Lee ST, Provenza FD and Reeve JR (2020) Do plant secondary metabolite-containing forages influence soil processes in pasture systems? *Agronomy Journal* **112**, 3744–3757. https://doi.org/10.1002/agj2.20361

Clemensen A, Villalba JJ, Lee S, Provenza F, Duke S and Reeve J (2022) How do tanniferous forages influence soil processes in forage cropping systems? *Crop, Forage & Turfgrass Management* **8**, e20166. https://doi.org/10.1002/cft2.20166

Cook BI, Mankin JS and Anchukaitis KJ (2018) Climate change and drought: from past to future. *Current Climate Change Reports* **4**, 164–179. https://doi.org/10.1007/s40641-018-0093-2

Copani G, Le Morvan GCA and Niderkorn V (2014) Bioactive forage legumes as a strategy to improve silage quality and minimise nitrogenous losses. *Animal Production Science* **54**, 1826–1829. http://doi.org/10.1071/AN14252

Copani G, Ginane C, Quereuil A, Anglard F and Niderkorn V (2015) *Benefit of Including Bioactive Legumes (Sainfoin, Red Clover) in Grass-Based Silages on Ruminant Production and Pollutant Emissions* (PhD thesis). Université Blaise Pascal, Vet Agro Sup, UMR Herbivores, Clermont-Ferrand, France.

Cornara L, Xiao J and Burlando B (2016) Therapeutic potential of temperate forage legumes: a review. *Critical Reviews in Food Science and Nutrition* **56**, 149–161. http://doi.org/10.1080/10408398.2015.1038378

Crews TE (1993) Phosphorus regulation of nitrogen fixation in a traditional Mexican agroecosystem. *Biogeochemistry* **21**, 141–166. https://doi.org/10.1007/BF00001115

Crews TE and Peoples MB (2004) Legume versus fertilizer sources of nitrogen: ecological tradeoffs and human needs. *Agriculture, Ecosystems & Environment* **102**, 279–297. https://doi.org/10.1016/j.agee.2003.09.018

Dai J and Mumper RJ (2010) Plant phenolics: extraction, analysis and their antioxidant and anticancer properties. *Molecules* **15**, 7313–7352. https://doi.org/10.3390/molecules15107313

Dash SS and Maity R (2023) Effect of climate change on soil erosion indicates a dominance of rainfall over LULC changes. *Journal of Hydrology: Regional Studies* **47**, 101373. https://doi.org/10.1016/j.ejrh.2023.101373

Decourtye A, Lecompte P, Pierre J, Chauzat MP and Thiébeau P (2007) Introduction de jachères florales en zones de grandes cultures – ou comment mieux concilier agriculture et biodiversité, et par conséquent, l'apiculture. *Le Courrier de l'Environnement de l'INRA* **54**, 33–56.

Decourtye A, Mader E and Desneux N (2010) Landscape enhancement of floral resources for honey bees in agro-ecosystems. *Apidologie* **41**, 264–277. https://doi.org/10.1051/apido/2010024

De Falco E, Landi G and Basso F (2000*a*) Production and quality of the sainfoin forage (*Onobrychis viciefolia* Scop.) as affected by cutting regime in a hilly area of southern Italy. *Cahiers Options Méditerranéennes* **45**, 275–279.

De Falco E, Landi G and Basso F (2000*b*) Production and quality of the sainfoin forage (*Onobrychis viaiaefolia* Scop.) as affected by cutting regime in a hilly area of southern Italy. In Sulas L (ed.), *Legumes for Mediterranean Forage Crops, Pastures and Alternative Uses*. Zaragoza: CIHEAM, pp. 275–279. (Cahiers Options Méditerranéennes; n. 45). 10. Meeting of the Mediterranean Sub-Network of the FAO-CIHEAM Inter-Regional Cooperative Research and Development Network on Pastures and Fodder Crops, 2000/04/04-09, Sassari (Italy). http://om.ciheam.org/om/pdf/c45/00600211.pdf

Dehabadi SRMH (1997) Biological point of view of water conservation under dryland condition. Proceedings of the 8th International Conference of Rainwater Catchment Systems, Vols 1 And 2. Soil Conservation & Watershed Management Research Center, pob 13445–1136, Tehran, Iran, pp. 840–847.

Dehabadi SRMH, Kemp PD, Barker DJ and Hodgson J (1993*a*) A comparison of sainfoin cultivars and lucerne, with an emphasis on sainfoin responses to water stress. *Proceedings Agronomy Society of New Zealand* **23**, 63–67.

Dehabadi SRMH, Kemp PD, Barker DJ and Hodgson J (1993*b*) Adaptation of sainfoin cultivars and lucerne to water stress. *Proceedings of the XVII International Grassland Congress*, pp. 158–159.

Deléglise C, Meisser M, Mosimann E, Spiegelberger T, Signarbieux C, Jeangros B and Buttler A (2015) Drought-induced shifts in plant traits, yields and nutritive value under realistic grazing and mowing managements in a mountain grassland. *Agriculture, Ecosystems and Environment* **213**, 94–104. https://doi.org/10.1016/jagee.2015.07.020

Demdoum S (2012) *Caracterización agronómica y composición química de una colección de variedades de Esparceta* (PhD thesis). Universidad de Lleida, Spain.

Demirci S and Özhatay N (2012) An ethnobotanical study in Kahramanmaraş (Turkey); wild plants used for medicinal purpose in Andirin, Kahramanmaraş. *Turkish Journal of Pharmaceutical Sciences* **9**, 75–92.

Desrues O, Mueller-Harvey I, Pellikaan WF, Enemark HL and Thamsborg SM (2017) Condensed tannins in the gastrointestinal tract of cattle after sainfoin (*Onobrychis viciifolia*) kinIntake and their possible relationship with anthelmintic effects. *Journal of Agricultural and Food Chemistry* **65**, 1420–1427. https://doi.org/10.1021/acs.jafc.6b05830

Deveci M and Kuvanci A (2012) Investigation of pollen preferences of honeybee. *Journal of Animal and Veterinary Advances* **11**, 1265–1269. https://doi.org/10.3923/javaa.2012.1265.1269

Dimitrova T (2010) Effect of weeds and some methods for their control in seed production stands of sainfoin (*Onobrychis viciifolia* Scop.). *Pesticides Phytomedicine (Belgrade)* **25**, 163–170. https://doi.org/10.2298/PIF1002163D

Dontas I, Halabalaki M, Moutsatsou P, Mitakou S, Papoutsi Z, Khaldi L, Raptou P, Galanos A and Lyritis GP (2006) Protective effect of plant extract from *Onobrychis ebenoides* on ovariectomy induced bone loss in rats. *Maturitas* **53**, 234–242. https://doi.org/10.1016/j.maturitas.2005.05.007

Doyle MP, Griffin JH, Bagheri V and Dorow RL (1984) Correlations between catalytic reactions of diazo compounds and stoichiometric reactions of transition-metal carbenes with alkenes. Mechanism of the cyclopropanation reaction. *Organometallics* **3**, 53–61. https://doi.org/10.1021/om00079a011

Drinkwater LE and Snapp SS (2007) Nutrients in agroecosystems: rethinking the management paradigm. *Advances in Agronomy* **92**, 163–186. https://doi.org/10.1016/S0065-2113(04)92003-2

East JD, Monier E, Saari RK and Garcia-Menendez F (2024) Projecting changes in the frequency and magnitude of ozone pollution events under uncertain climate sensitivity. *Earth's Future* **12**, e2023EF003941. https://doi.org/10.1029/2023EF003941

Eekhout JPC and de Vente J (2022) Global impact of climate change on soil erosion and potential for adaptation through soil conservation. *Earth-Science Reviews* **226**, 103921. https://doi.org/10.1016/j.earscirev.2022.103921

Eken C, Demirci E and Dane E (2004) Species of *Fusarium* on sainfoin in Erzurum, Turkey. *New Zealand Journal of Agricultural Research* **47**, 261–263. http://doi.org/10.1080/00288233.2004.9513593

El Sabagh A, Islam MS, Skalicky M, Ali Raza M, Singh K, Anwar Hossain M, Hossain A, Mahboob W, Iqbal M, Ratnasekera D, Singhal RK, Ahmed S, Kumari A, Wasaya A, Sytar O, Brestič M, Çığ F, Erman M, Habib ur Rahman M, Ullah N and Arshad A (2021) Salinity stress in wheat (*Triticum aestivum* L.) in the changing climate: adaptation and management strategies. *Frontiers in Agronomy* **3**, 661932. https://doi.org/10.3389/fagro.2021.661932

Faergeman O (2007) Climate change and preventive medicine. *European Journal of Cardiovascular Prevention and Rehabilitation* **14**, 726–729. https://doi.org/10.1097/HJR.0b013e3282f30097

Falistocco E (1991) Chromosome study and genome relationships in perennial species of *Onobrychis*. *Journal of Genetics and Breeding* **45**, 25–32.

FAO (2020) *The State of Food Security and Nutrition in the World 2020. Transforming Food Systems for Affordable Healthy Diets*. Rome: FAO. Available at http://www.fao.org/3/ca9692en/ca9692en.pdf

Feng X, Thompson SE, Woods R and Porporato A (2019) Quantifying asynchronicity of precipitation and potential evapotranspiration in Mediterranean climates. *Geophysical Research Letters* **46**. https://doi.org/10.1029/2019GL085653

Ferreira CSS, Seifollahi-Aghmiuni S, Destouni G, Ghajarnia N and Kalantari Z (2022) Soil degradation in the European Mediterranean region: processes, status and consequences. *Science of the Total Environment* **805**, 150106. https://doi.org/10.1016/j.scitotenv.2021.150106

Ferret M (1975) Comportement des espèces et variétés fourragères autres que la luzerne en zone méditerranéenne. *Fourrages* **64**, 103–114.

Field J and Lettinga G (1992) Toxicity of tannic compounds to microorganisms. In Hemingway RW and Laks PE (eds), *Plant Polyphenols* (Basic life sciences vol. 59). New York, NY: Springer, pp. 673–692. https://doi.org/10.1007/978-1-4615-3476-1_39

Folly AJ, Koch H, Farrell IW, Stevenson PC and Brown MJF (2021) Agrienvironment scheme nectar chemistry can suppress the social epidemiology of parasites in an important pollinator. *Proceedings of the Royal Society B* **288**, 20210363. https://doi.org/10.1098/rspb.2021.0363

Frame J (2005) *Forage Legumes for Temperate Grasslands*. Enfield, NH: FAO, Science Publishers, Inc., 309pp.

Frame J, Charlton JFL and Laidlaw AS (1998) *Temperate Forage Legumes*. Great Britain: CAB International.

García Salmerón J, Montserrat P, Buendía F, Ruiz-del-Castillo A and Allue J (1966) *Studies of Botany, Ecology, Biology and Pascology of the Principal Existing Species in the Spontaneous Pasture-Grounds of Mountains of our Semiarid Regions*. Madrid, España: Instituto Forestal de Investigaciones y Experiencias. https://doi.org/10.1111/j.1744-7348.2004.tb00343.x

Gaudin E (2017) *Le sainfoin déshydraté: Un modèle de nutricament dans la lutte contre les nématodes parasites des petits ruminants* (Thèse d, France: Université INP Toulouse). soutenue le 16 mai 2017.

Gaudin E, Costes-Thiré M, Villalba JJ, Hoste H, Gerfault V and Ginane C (2019) Relative abilities of young sheep and goats to self-medicate with tannin-rich sainfoin when infected with gastrointestinal nematodes. *Animal* **13**, 1498–1507. https://doi.org/10.1017/S175173111800304X

Gayrard C, Gombault P, Bretaudeau A, Hoste H and Gidenne T (2021) Nutritive value of dehydrated sainfoin (*Onobrychis viciifolia*) for growing rabbits, according to the harvesting stage. *Animal Feed Science and Technology* **279**, 114995. https://doi.org/10.1016/j.anifeedsci.2021.114995

Girard M, Dohme-Meier F, Wechsler D, Kreuzer M and Bee G (2015) Comparison of effects of forage containing condensed tannins on milk and cheese quality. *Proceedings of the 66th meeting of the European Federation of Animal Science (EAAP)*, 31st Aug to 4th Sep, Warsaw, Poland, p. 375.

Girard M, Dohme-Meier F, Wechsler D, Goy D, Kreuzer M and Bee G (2016) Ability of 3 tanniferous forage legumes to modify quality of milk and Gruyère-type cheese. *Journal of Dairy Science* **99**, 205–220. http://doi.org/10.3168/jds.2015-9952

Godde CM, Mason DD, Mayberry DE, Thornton PK and Herrero M (2021) Impacts of climate change on the livestock food supply chain; a review of the evidence. *Global Food Security* **28**, 100488. https://doi.org/10.1016/j.gfs.2020.100488

Goldblatt P (1981) Index to plant chromosome numbers 1975–1978. Monog Syst Botan. 5. Saint Louis Missouri. 553p.

González E, ŠtroblŠtrobl M, Janšta P, Hovorka T, Kadlec T and Knapp M (2022) Artificial temporary non-crop habitats support parasitoids on arable land. *Biological Conservation* **265**, 109409. https://doi.org/10.1016/j.biocon.2021.109409

Goplen BP, Richards KW and Moyer JR (1991) *Sainfoin for Western Canada*. Ottawa, ON: Agriculture Canada Publication, 1470/E.

Gremer JR, Chiono A, Suglia E, Bontrager M, Okafor L and Schmit J (2020) Variation in the seasonal germination niche across an elevational gradient: the role of germination cueing in current and future climates. *American Journal of Botany* **107**(2), 350–363. https://doi.org/10.1002/ajb2.1425

Guglielmelli A, Calabro S, Primi R, Carone F, Cutrignelli MI, Tudisco R, Piccolo G, Ronchi B and Danieli PP (2011) *In vitro* fermentation patterns and methane production of sainfoin (*Onobrychis viciifolia* Scop.) hay with different condensed tannin contents. *Grass and Forage Science* **66**, 488–500. http://doi.org/10.1111/j.1365-2494.2011.00805.x

Gullino ML, Albajes R, Al-Jboory I, Angelotti F, Chakraborty S, Garrett KA, Hurley BP, Juroszek P, Lopian R, Makkouk K, Pan X, Pugliese M and Stephenson T (2022) Climate change and pathways used by pests as challenges to plant health in agriculture and forestry. *Sustainability* **14**, 12421. https://doi.org/10.3390/su141912421

Hanna MR and Smoliak S (1968) Sainfoin yield evaluation ln Canada. In Cooper CS and Car1eton AE (eds), « *Sainfoin Symposium* », Vol. **627**. Montana Agriculture Experiment Station Bulletin, Montana, Agric. Exp. Stn., Bozeman, MT, pp. 38–13.

Harris JA, Hobbs RJ, Higgs E and Aronson J (2006) Ecological restoration and global climate change. *Restoration Ecology* **14**, 170–176. https://doi.org/10.1111/j.1526-100X.2006.00136.x

Hatew B, Hayot Carbonero C, Stringano E, Sales LF, Smith LMJ, Mueller-Harvey I, Hendriks WH and Pellikaan WF (2015) Diversity of condensed tannin structures affects rumen *in vitro* methane production in sainfoin (*Onobrychis viciifolia*) accessions. *Grass and Forage Science* **70**, 474–490. https://doi.org/10.1111/gfs.12125

Hatew B, Stringano E, Mueller-Harvey I, Hendriks WH, Hayot-Carbonero C, Smith LMJ and Pellikaan WF (2016) Impact of variation in structure of condensed tannins from sainfoin (*Onobrychis viciifolia*) on *in vitro* ruminal methane production and fermentation characteristics. *Journal of Animal Physiology and Animal Nutrition* **100**, 348–360. https://doi.org/10.1111/jpn.12336

He J, Tian D, Li X, Wang X, Wang T, Wang Z, Zang H, He X, Zhang T, Yun Q, Zhang R, Jiang J, Jia S and Zhang Y (2024) A chromosome-level genome assembly for *Onobrychis viciifolia* reveals gene copy number gain underlying enhanced proanthocyanidin biosynthesis. *Communications Biology* **7**, 19. https://doi.org/10.1038/s42003-023-05754-6

Herrera JM, Rubio G, Häner LL, Delgado JA, Lucho-Constantino CA, Islas-Valdez S and Pellet D (2016) Emerging and established technologies to increase nitrogen use efficiency of cereals. *Agronomy* **6**, 25. https://doi.org/10.3390/agronomy6020025

Hill NS (1980) *An Evaluation of Factors Affected by Nitrogen Fixation in Sainfoin (Onobrychis viciifolia Scop)* (Master thesis). Montana State University, Bozeman, 35pp.

Hill R (1997) Sainfoin: the not quite forgotten legume. In Lane GPF and Wilkinson JM (eds), *Alternative Forages for Ruminants*. Cirencester: Papers, Conference, pp. 55–59.

Horne M (1995) Pollen preference and its relationship to nesting success of *Megachile rotundata* (*Hymenoptera*, *Megachilidae*). *Annals of the Entomological Society of America* **88**, 862–867. https://doi.org/10.1093/aesa/88.6.862

Hoste H and Niderkorn V (2019) Le sainfoin (*Onobrychis viciifolia*) et la chicorée (*Cichorium intybus*): deux modèles de plantes bioactives pour répondre aux défis agroécologiques en élevage de ruminants. *Fourrages, Association Française pour la Production Fourragère* **238**, 171–180.

Hoste H, Torres-Acosta JFJ, Sandoval-Castro CA, Mueller-Harvey I, Sotiraki S, Louvandini H, Thamsborg SM and Terrill TH (2015) Tannin containing legumes as a model for nutraceuticals against digestive parasites in livestock. *Veterinary Parasitology* **212**, 5–17.

Howes FN (2007) *Plants and Beekeeping*. London: Faber & Faber, p. 260.

Huang Z, Liu Y, Tian FP and Wu GL (2020) Soil water availability threshold indicator was determined by using plant physiological responses under drought conditions. *Ecological Indicators* **118**, 106740. https://doi.org/10.1016/j.ecolind.2020.106740

Hume LJ and Withers NJ (1985) Nitrogen fixation in sainfoin (*Onobrychis viciifolia*) 1. responses to changes in nitrogen nutrition. *New Zealand Journal of Agricultural Research* **28**, 325–335. https://doi.org/10.1080/00288233.1985.10430435

Hunady I, Ondriskova V, Hutyrova H, Kubikova Z, Hammerschmiedt T and Mezera J (2021) Use of wild plant species: a potential for methane production in biogas plants. *International Journal of Renewable Energy Research* **11**, 920–932.

Hur S, Kim J, Yim D, Yoon Y, Lee S and Jo C (2024) Impact of livestock industry on climate change: case study in South Korea – a review. *Animal Bioscience* **37**, 405–418. https://doi.org/10.5713/ab.23.0256

Hutchinson J (1966) Land and Human Population. *Nature* **211**, 1053–1055. https://doi.org/10.1038/2111053a0

Huyen N, Fryganas C, Uittenbogaard G, Mueller-Harvey I, Verstegen M, Hendriks W and Pellikaan W (2016*a*) Structural features of condensed tannins affect *in vitro* ruminal methane production and fermentation characteristics. *The Journal of Agricultural Science* **154**, 1474–1487. https://doi.org/10.1017/S0021859616000393

Huyen NT, Desrues O, Alferink SJJ, Zandstra T, Verstegen MWA, Hendriks WH and Pellikaan WF (2016*b*) Inclusion of sainfoin (*Onobrychis viciifolia*) silage in dairy cow rations affects nutrient digestibility, nitrogen utilization, energy balance, and methane emissions. *Journal of Dairy Science* **99**, 3566–3577. http://doi.org/10.3168/jds.2015-10583

Ibragimov KM, Gamidov IR and Umakhanov MA (2019) Productivity of Hungarian sainfoin in two and three-component grass mixtures for vegetative reclamation on Kizlyar grasslands. *Feed Production* **7**, 23–27.

Intergovernmental Panel on Climate Change (IPCC) (2021) Climate change 2021: the physical science basis. In Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R and Zhou B (eds), *Contribution of Working Group to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, New York, NY: Cambridge University Press, p. 2391.

Irani S, Majidi MM, Mirlohi A, Zargar M and Karami M (2015*a*) Assessment of drought tolerance in sainfoin: physiological and drought tolerance indices. *Agronomy Journal* **107**, 1771. https://doi.org/10.2134/agronj15.0131

Irani S, Majidi MM, Mirlohi A, Karami M and Zargar M (2015*b*) Response to drought stress in sainfoin: within and among ecotype variation. *Crop Science* **55**, 1868–1880. http://doi.org/10.2135/cropsci2014.07.0481

Issah G, Schoenau JJ, Lardner HA and Knight JD (2020) Nitrogen fixation and resource partitioning in alfalfa (*Medicago sativa* L.), Cicer Milkvetch (*Astragalus cicer* L.) and Sainfoin (*Onobrychis viciifolia* Scop.) using ^{15}N enrichment under controlled environment conditions. *Agronomy* **10**, 1438. https://doi.org/10.3390/agronomy10091438

ISTAT (2013) *Dati annuali sulle coltivazioni*. [Online]. Roma: ISTAT. Available at http://agri.istat.it (19 March 2013).

Jafari AA, Rasoli M, Tabaei-Aghdaei SR, Shanjani PS and Alizadeh MA (2014) Evaluation of herbage yield, agronomic traits and powdery mildew disease in 35 populations of sainfoin (*Onobrychis sativa*) across 5 environments of Iran. *Romanian Agricultural Research* **31**, 41–48.

Jensen EH, Torelli CR, Lesperance AI and Speth CF (1968) Evaluation of sainfoin and alfalfa with beef cattle. In Cooper CS and Car1eton AE (eds), « *Sainfoin Symposium* », Vol. **627**. Montana Agriculture Experiment Station Publications: Bulletin, pp. 100–101.

Jensen ES, Peoples MB, Boddey RM, Gresshoff PM, Henrik HN, Alves BJR and Morrison MJ (2012) Legumes for mitigation of climate change and the provision of feedstock for biofuels and biorefineries. A review. *Agronomy for Sustainable Development* **32**, 329–364. https://doi.org/10.1007/s13593-011-0056-7

Jiang Y, Xu Z, Zhou G and Tao L (2016) Elevated CO_2 can modify the response to a water status gradient in a steppe grass: from cell organelles to photosynthetic capacity to plant growth. *BMC Plant Biology* **16**, 157. https://doi.org/10.1186/s12870-016-0846-9

Jin Z, Jiang W, Yi D and Pang Y (2021) The complete chloroplast genome sequence of sainfoin (*Onobrychis viciifolia*). *Mitochondrial DNA Part B* **6**, 496–498. https://doi.org/10.1080/23802359.2020.1871439

Jing Z, Liu N, Zhang Z and Hou X (2024) Research progress on plant responses to stress combinations in the context of climate change. *Plants* **13**, 469. https://doi.org/10.3390/plants13040469

Joanisse GD, Bradley RL, Preston CM and Munson and AD (2007) Soil enzyme inhibition by condensed litter tannins may drive ecosystem structure and processes: the case of *Kalmia angustifolia*. *New Phytologist* **175**, 535–546. https://doi.org/10.1111/j.1469-8137.2007.02113.x

Kadri A, Chaabena A, Abdelguerfi A and Laouar M (2021) Influence of salinity on germination and early seedling root growth traits of alfalfa (*Medicago sativa* L.) landraces collected in Southern Algerian oases. *Agriculture and Natural Resources* **55**, 976–985. https://doi.org/10.34044/j.anres.2021.55.6.08

Kallenbach RL, Matches AG and Mahan JR (1996) Sainfoin regrowth declines as metabolic rate increases with temperature. *Crop Science* **36**, 91–97. https://doi.org/10.2135/cropsci1996.0011183X003600010017x

Kaplan M (2011) Determination of potential nutritive value of sainfoin (*Onobrychis viciifolia* Scop.) hays harvested at flowering stage. *Journal of Animal and Veterinary Advances* **10**, 2028–2031. http://doi.org/10.3923/javaa.2011.2028.2031

Karakoca K, Asan-Ozusaglam M, Cakmak YS and Teksen M (2015) Phenolic compounds, biological and antioxidant activities of *Onobrychis armena* Boiss. & huet flower and root extracts. *Chiang Mai Journal of Science* **42**, 376–392.

Karamian R and Asadbegy M (2016) Antioxidant activity, total phenolic and flavonoid contents of three *Onobrychis* Species from Iran. *Pharmaceutical Sciences* **22**, 112–119.

Karamian R and Ataei-Barazande S (2013) Effect of salinity on some growth parameters in three *Onobrychis* species (*Fabaceae*) in Iran. *Iraniain Journal of Plant Biology* **5**, 69–81.

Karatassiou M, Noitsakis B and Koukoura Z (2009) Drought adaptation eco-physiological mechanisms of two annual legumes on semi-arid Mediterranean grassland. *Scientific Research and Essay* **4**, 493–500.

Kells A (2001) Sainfoin: an alternative forage crop for bees. *Bee World* **82**, 192–194. https://doi.org/10.1080/0005772X.2001.11099526

Kempf K (2016) *Self-Fertilization and Marker-Trait Associations in Sainfoin (Onobrychis viciifolia)*. PhD thesis, University of Hohenheim, Hohenheim, Germany. ETH Zurich.

Khalilvandi-Behroozyar H, Dehghan-Banadaky M and Rezayazdi K (2010) Palatability, *in situ* and *in vitro* nutritive value of dried sainfoin (*Onobrychis viciifolia*). *The Journal of Agricultural Science* **148**, 723–733. https://doi.org/10.1017/S0021859610000523

Kintl A, Huňady I, Vymyslický T, Ondrisková V, Hammerschmiedt T, Brtnický M and Elbl J (2021) Effect of seed coating and PEG-induced drought on the germination capacity of five clover crops. *Plants* **10**, 724. https://doi.org/10.3390/plants10040724

Koch DW, Dotzenko AD and Hinze GO (1972) Influence of three systems on the yield, water use efficiency, and forage quality of sainfoin. *Agronomy Journal* **64**, 463–467.

Koivisto JM and Lane GPF (2001) Sainfoin-Worth another Look. Forage Matters 6.

Komainda M, Küchenmeister K, Küchenmeister F, Breitsameter L, Wrage-Mönnig N, Kayser M and Isselstein J (2019) Forage legumes for future dry climates: lower relative biomass losses of minor forage legumes compared to *Trifolium repens* under conditions of periodic drought stress. *Journal of Agronomy and Crop Science* **205**, 460–469. https://doi.org/10.1111/jac.12337

Komáromyová M, Mravčáková D, Petrič D, Kucková K, Babják M, Urda Dolinská M, Königová A, Maďarová M, Pruszyńska-Oszmałek E, Cieslak A, Čobanová K, Váradyová Z, Várady M (2021) Effects of medicinal plants and organic selenium against ovine haemonchosis. *Animals* **11**(5), p. 1319. https://doi.org/10.3390/ani11051319

Kon KF (1980) *Dual Mutualistic Associations in Sainfoin (Onobrychis viciifolia* Scop.*) (Master of Agricultural Science in Agronomy)*. New Zealand: Massey University.

Kong J, Pei Z, Du M, Sun G and Zhang X (2014) Effects of arbuscular mycorrhizal fungi on the drought resistance of the mining area repair plant Sainfoin. *International Journal of Mining Science and Technology* **24**, 485–489. https://doi.org/10.1016/j.ijmst.2014.05.011

Kretz L, Seele C, van der Plas F, Weigelt A and Wirth C (2020) Leaf area and pubescence drive sedimentation on leaf surfaces during flooding. *Oecologia* **193**, 535–545. https://doi.org/10.1007/s00442-020-04664-2

Kropacova S and Haslbachova H (1969) Study of the honey bee foraging on sainfoin plants (*Onobrychis viciaefolia*, Thell). *Proceedings of the 22nd International Apicultural Congress*, Munich, pp. 476–477.

Kumar V, Srivastava AK, Sytar O and Penna S (2023) Editorial: plants for future climate: responses and adaptations to combined, multifactorial, and sequential stresses. *Frontiers in Plant Science* **14**, 1290649. https://doi.org/10.3389/fpls.2023.1290649

Ladha JK, Pathak H, Krupnik TJ, Six J and van Kessel C (2005) Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. *Advances in Agronomy* **87**, 85–156. https://doi.org/10.1016/S0065-2113(05)87003-8

Lagrange S, Beauchemin KA, MacAdam J and Villalba JJ (2020) Grazing diverse combinations of tanniferous and non-tanniferous legumes: implications for beef cattle performance and environmental impact. *Science of the Total Environment* **746**, 140788. https://doi.org/10.1016/j.scitotenv.2020.140788

Lagrange SP, MacAdam JW and Villalba JJ (2021) The use of temperate tannin containing forage legumes to improve sustainability in forage-livestock production. *Agronomy* **11**, 2264. https://doi.org/10.3390/agronomy11112264

Lal R (2012) Climate change and soil degradation mitigation by sustainable management of soils and other natural resources. *Agricultural Research* **1**, 199–212. https://doi.org/10.1007/s40003-012-0031-9

Le Conte Y and Navajas M (2008) Climate change: impact on honey bee populations and diseases. *Revue scientifique et technique-Office International des Epizooties* **27**, 499–510.

Lee MRF, Scott MB, Tweed JKS, Minchin FR and Davies DR (2008) Effects of polyphenol oxidase on lipolysis and proteolysis of red clover silage with and without a silage inoculant (*Lactobacillus plantarum* L54). *Animal Feed Science and Technology* **144**, 125–136. http://doi.org/10.1016/j.anifeedsci.2007.09.035

Legendre H, Goby JP, Duprat A, Gidenne T and Martin G (2019) Herbage intake and growth of rabbits under different pasture type, herbage allowance and quality conditions in organic production. *Animal* **13**, 495–501. https://doi.org/10.1017/s1751731118001775

Le Houérou HN (1969) La végétation de la Tunisie steppique (1) (Structure, écologie, sociologie, répartition, évolution, utilisation, biomasse, productivité) (avec référence aux végétations analogues d'Algérie, de Libye et du Maroc). *Annales de l'Institut National de la Recherche Agronomique de la Tunisie* **42**, 622.

Lesk C, Rowhani P and Ramankutty N (2016) Influence of extreme weather disasters on global crop production. *Nature* **529**, 84–87. https://doi.org/10.1038/nature16467

Li RSHIF, Fukuda K and Yang Y (2010) Effects of salt and alkali stresses on germination, growth, photosynthesis and ion accumulation in alfalfa (*Medicago sativa* L.). *Soil Science and Plant Nutrition* **56**, 725–733. https://doi.org/10.1111/j.1747-0765.2010.00506.x

Li M, Wu P, Sexton DMH, and Ma Z (2021*a*) Potential shifts in climate zones under a future global warming scenario using soil moisture classification. *Climate Dynamics* **56**, 2071–2092. https://doi.org/10.1007/s00382-020-05576-w

Li SJ, Zhu YH, White JF, Wei M and Wu GQ (2021*b*) Two sainfoin (*Onobrychis viciifolia* Scop.) cultivars differ in their responses to neutral and saline-alkali stress during seed germination and early seedling growth. *Applied Ecology and Environmental Research* **19**, 4299–4311. http://doi.org/10.15666/aeer/1906_42994311

Liu Z, Lane GPF and Davies WP (2006) The effects of establishment method on the yield of sainfoin (*Onobrychis viciifolia*) and sainfoin –grass mixtures. *Proceedings of British Grassland Society 8th Research Conference*.

Liu Z, Baines RN, Lane GPF and Davies WP (2010) Survival of plants of common sainfoin (*Onobrychis viciifolia* Scop.) in competition with two companion grass species. *Grass and Forage Science* **65**, 11–14. https://doi.org/10.1111/j.1365-2494.2009.00714.x

Liu XL, Hao YQ, Jin L, Xu ZJ, McAllister TA and Wang Y (2013) Anti-*Escherichia coli* O157:H7 properties of purple prairie clover and sainfoin condensed tannins. *Molecules* **18**, 2183–2199. https://doi.org/10.3390/molecules18022183

Liu JG, Cui WH, Tian Z and Jia JL (2020) Theory of stepwise ecological restoration. *Chinese Science Bulletin* **66**, 1014–1025. https://doi.org/10.1360/TB-2020-1128

Lock JM (2005) Tribe Hedysarae. In Lewis G, Schrire B, Mackinder B and Lock M (eds), *Legumes of the World*. Kew: Royal Botanical Gardens, pp. 489–495.

Lock JM and Simpson K (1991) *Legumes of West Asia, a Check-List*. Kew: Royal Bot. Gardens.

Lorenz M (2011) *Sainfoin Tannins and Their Impact on Protein Degradation During Silage and Rumen Fermentation and Testing of Novel Techniques*. Uppsala: Swedish University of Agricultural Sciences.

Lorenz M, Eriksson T and Udén P (2010) Effect of wilting, silage additive, PEG treatment and tannin content on the distribution of N between different fractions after ensiling of three different sainfoin (*Onobrychis viciifolia*) varieties. *Grass and Forage Science* **65**, 175–184. http://doi.org/10.1111/j.1365-2494.2010.00736.x

Mabberley DJ (1997) *The Plant Book. A Portable Dictionary of the Vascular Plants*, 2nd Edn. Cambridge: Cambridge Univ. Press.

Mabberley DJ (2008) *The Plant-Book. A Portable Dictionary of the Higher Plants*, 3rd Edn. Cambridge, UK: Cambridge University Press.

Majidi MM and Barati M (2011) Methods for breaking seed dormancy in one cultivated and two wild *Onobrychis* species. *Seed Science and Technology* **39**, 44–53. http://doi.org/10.15258/sst.2011.39.1.05

Malisch CS, Lüscher A, Baert N, Engström MT, Studer B, Fryganas C, Suter D, Mueller-Harvey T and Salminen JP (2015) Large variability of proanthocyanidin content and composition in sainfoin (*Onobrychis viciifolia*). *Journal of Agricultural and Food Chemistry* **63**, 10234–10242. https://doi.org/10.1021/acs.jafc.5b04946

Malisch CS, Salminen JP, Kölliker R, Engström M, Suter D, Studer B and Lüscher A (2016) Drought effects on proanthocyanidins in sainfoin (*Onobrychis viciifolia* Scop.) are dependent on the plant's ontogenetic stage. *Journal of Agricultural and Food Chemistry* **64**, 9307–9316. https://doi.org/10.1021/acs.jafc.6b02342

Malisch CS, Suter D, Studer B and Lüscher A (2017) Multifunctional benefits of sainfoin mixtures: effects of partner species, sowing density and cutting regime. *Grass and Forage Science* **72**, 794–805. https://doi.org/10.1111/gfs.12278

Mandal D, Giri N and Srivastava P (2020) The magnitude of erosion-induced carbon (C) flux and C-sequestration potential of eroded lands in India. *European Journal of Soil Science* **71**, 151–168. https://doi.org/10.1111/ejss.12886

Manino A, Patetta A, Boglietti G and Porporato M (2010) Bumble bees of the Susa Valley (*Hymenoptera Apidae*). *Bulletin of Insectology* **63**, 137–152.

Marais JP, Mueller-Harvey I, Brandt EV and Ferreira D (2000) Polyphenols, condensed tannins, and other natural products in *Onobrychis viciifolia* (Sainfoin). *Journal of Agricultural and Food Chemistry* **48**, 3440–3447. https://doi.org/10.1021/jf000388h

March-Salas M, van Kleunen M and Fitze PS (2021) Effects of intrinsic precipitation-predictability on root traits, allocation strategies and the selective regimes acting on them. *Oikos*, **2022**(1), e07970. https://doi.org/10.1111/oik.07970

Marten GC, Ehle FR and Ristau EA (1987) Performance andphotosensitization of cattle related to forage quality offour legumes. *Crop Science* **27**, 138–145.

Martin G, Duprat A, Goby JP, Theau JP, Roinsard A, Descombes M, Legendre H and Gidenne T (2016) Herbage intake regulation and growth of rabbits raised on grasslands: back to basics and looking forward. *Animal* **10**, 1609–1618. https://doi.org/10.1017/S1751731116000598

Martini E (1981) La fitoterapia popolare in Val Borbera (Appennino Ligure). *Webbia* **35**, 187–205. https://doi.org/10.1080/00837792.1981.10670218

Martins-Noguerol R, Moreno-Pérez AJ, Pedroche J, Gallego-Tévar B, Cambrollé J, Matías L, Fernández-Rebollo P, Martínez-Force E and Pérez-Ramos IM (2023) Climate change alters pasture productivity and quality: impact on fatty acids and amino acids in Mediterranean silvopastoral ecosystems. *Agriculture, Ecosystems & Environment* **358**, 108703. https://doi.org/10.1016/j.agee.2023.108703

Mathre D (1968) Disease in sainfoin. In Cooper CS and Carleton AE (eds), *Sainfoin Symposium*, Vol. **627**. Montana Agriculture Experiment Station Publications: Bulletin, pp. 65–66.

Matzrafi M, Brunharo C, Tehranchian P, Hanson BD and Jasieniuk M (2019) Increased temperatures and elevated CO_2 levels reduce the sensitivity of *Conyza canadensis* and *Chenopodium album* to glyphosate. *Scientific Reports* **9**, 2228. https://doi.org/10.1038/s41598-019-38729-x

Mbaveng AT, Hamm R and Kuete V (2014) Harmful and protective effects of terpenoids from African medicinal plants. In Victor Kuete (ed.), *Toxicological Survey of African Medicinal Plants*. Amsterdam, The Netherlands: Elsevier, pp. 557–576. https://doi.org/10.1016/C2013-0-15406-2

McCordick SA, Hillger DE, Leep RL and Kells JJ (2008) Establishment systems for glyphosate-resistant alfalfa. *Weed Technology* **22**, 22–29.

McGregor SE (1976) Insect pollination of cultivated crop plants, Chapter 4 in 'Legumes and Some Relatives'. USDA Agriculture Handbook, 496, pp. 93–98. Available at http://gears.tucson.ars.ag.gov/book/

McMahon LR, Majak W, Mcallister TA, Hall JW, Jones GA, Popp JD and Cheng KJ (1999) Effect of sainfoin on *in vitro* digestion of fresh alfalfa and bloat in steers. *Canadian Journal of Animal Science* **79**, 203–212. https://doi.org/10.4141/A98-074

Mehrabi HR and Chaichi MR (2012) Effect of Seed Coating Methods on Germination Speed of *Onobrychis sativa* at Different Drought Stress Levels and Sowing Depths. *International Conference on Future Environment and Energy IPCBEE* vol. 28 (2012) © (2012). Singapore: IACSIT Press.

Mercier JF, Tracy BL, d'Amours R, Chagnon F, Hoffman I, Korpach EP, Johnson S and Ungar RK (2009) Increased environmental gamma-ray dose rate during precipitation: a strong correlation with contributing air mass. *Journal of Environmental Radioactivity* **100**(7), 527–533. https://doi.org/10.1016/j.jenvrad.2009.03.002

Mganga KZ, Razavi BS, Sanaullah M and Kuzyakov Y (2019) Phenological stage, plant biomass, and drought stress affect microbial biomass and enzyme activities in the rhizosphere of *Enteropogon macrostachyus*. *Pedosphere* **29**, 259–265. https://doi.org/10.1016/S1002-0160(18)60799-X

Millennium Ecosystem Assessment (2005) *Ecosystems and Human Well-Being: Synthesis*. Island Press, Washington DC: Millennium Ecosystem Assessment. Retrieved 14 October 2009 from http://www.maweb.org/documents/document.356.aspx.pdf

Miller DA and Hoveland CS (1995) *Other Temperate Legumes*. Ames, IA, USA: Iowa State University Press.

Minnee EMK, Woodward SL, Waghorn GC and Laboyrie PG (2002) The effect of ensiling forage legumes on condensed tannins. *Agronomy New Zealand* **32/33**, 117–119.

Molan AL, Hoskin SO, Barry TN and McNabb WC (2000*a*) Effect of condensed tannins extracted from four forages on the viability of the larvae of deer lungworms and gastrointestinal nematodes. *Veterinary Record* **147**, 44–48.

Molan AL, Waghorn GC, Min BM and McNabb WC (2000*b*) The effect of condensed tannins from seven herbages on *Trichostrongylus colubriformis* larval migration *in vitro*. *Folia Parasitologica* **47**, 39–44.

Molan AL, Waghorn GC and McNabb WC (2002) Effect of condensed tannins on egg hatching and larval development of *Trichostrongylus colubriformis in vitro*. *Veterinary Record* **150**, 65–69. https://doi.org/10.1136/vr.150.3.65

Mondal S (2021) Impact of climate change on soil fertility. In Choudhary DK, Mishra A and Varma A (eds), *Climate Change and the Microbiome. Soil Biology*, Vol. **63**. Cham: Springer, pp. 551–569. https://doi.org/10.1007/978-3-030-76863-8_28

Mondoni A, Jiménez-Alfaro B and Cavieres LA (2022) Chapter 1 – effect of climate change on plant regeneration from seeds in the Arctic and alpine biome. In Baskin CC and Baskin JM (eds), *Plant Regeneration from Seeds*. United States: Academic Press, pp. 3–18. https://doi.org/10.1016/B978-0-12-823731-1.00007-X

Moore AD and Ghahramani A (2013) Climate change and broadacre livestock production across southern Australia. 1. impacts of climate change on pasture and livestock productivity, and on sustainable levels of profitability. *Global Change Biology* **19**, 1440–1455. https://doi.org/10.1111/gcb.12150

Mora-Ortiz M and Smith LMJ (2018) *Onobrychis viciifolia*: a comprehensive literature review of its history, etymology, taxonomy, genetics, agronomy and botany. *Plant Genetic Resources: Characterization and Utilization* **16**, 403–418. https://doi.org/10.1017/S1479262118000230

Mora-Ortiz M, Swain MT, Vickers MJ, Hegarty MJ, Kelly R, Smith LMJ and Skøt L (2016) De-novo transcriptome assembly for gene identification, analysis, annotation, and molecular marker discovery in *Onobrychis viciifolia*. *BMC Genomics* **17**, 1–13. https://doi.org/10.1186/s12864-016-3083-6

Morrill WL, Ditterline RL and Cash SD (1998) Insect pests and associated root pathogens of sainfoin in western USA. *Field Crops Research* **59**, 129–134. https://doi.org/10.1016/S0378-4290(98)00113-0

Moyer JR (1985) Effect of weed control and a companion crop on alfalfa and sainfoin establishment, yields and nutrient composition. *Canadian Journal of Plant Science* **65**, 107–116. https://doi.org/10.4141/cjps85-015

Mueller-Harvey I, Bee G, Dohme-Meier F, Hoste H, Karonen M, Kölliker R, Lüscher A, Niderkorn V, Pellikaan WF, Salminen JP and Skøt L (2019) Benefits of condensed tannins in forage legumes fed to ruminants: importance of structure, concentration, and diet composition. *Crop Science* **59**, 861–885. https://doi.org/10.2135/cropsci2017.06.0369

Mummey DL and Ramsey PW (2017) Can sainfoin improve conditions for establishment of native forbs in crested wheatgrass stands? *Ecological Restoration* **35**, 127–137. https://doi.org/10.3368/er.35.2.127

Munda S, Munda S, Nayak BK, Das SR, Dey S, Pradhan A, Swain CK and Muduli BC (2024) Understanding the effects of changing climate on weeds and their management. In Pathak H, Chatterjee D, Saha S and Das B (eds), *Climate Change Impacts on Soil-Plant-Atmosphere Continuum. Advances in Global Change Research*, Vol. **78**, pp. 405–425. Singapore: Springer. https://doi.org/10.1007/978-981-99-7935-6_15

Nasirzadeh AR, Khorram SM and Heydari SH (2005) Study of physiological effects of dehydration (drought) stress on vegetative growth of six species of sainfoin (*Onobrychis*). *Genetic Research and Breeding of Rangeland and Forest Plants in Iran* **12**, 365–375 (in Persian). https://doi.org/10.22092/IJRFPBGR.2005.115397

Ndukwu MC and Onyeoziri CI (2022) African oil bean seed as feedstock for bio-oil and biodiesel production and on the effects of thermal pretreatments on the quality of the bio-oil. *Biomass Conversion and Biorefinery* **12**, 2799–2810. https://doi.org/10.1007/s13399-020-00754-6

Niderkorn V, Baumont R, Le Morvan A and Macheboeuf D (2011) Occurrence of associative effects between grasses and legumes in binary mixtures on *in vitro* rumen fermentation characteristics. *Journal of Animal Science* **89**, 1138–1145. https://doi.org/10.2527/jas.2010-2819

Niderkorn V, Mueller-Harvey I, Le Morvan A and Aufrère J (2012) Synergistic effects of mixing cocksfoot and sainfoin on *in vitro* rumen fermentation. Role of condensed tannins. *Animal Feed Science and Technology* **178**, 48–56. http://doi.org/10.1016/j.anifeedsci.2012.09.014

Niderkorn V, Copani G and Ginane C (2016) Including bioactive legumes in grass silage to improve productivity and reduce pollutant emissions. *26th General Meeting of the European Grassland Federation*, Trondheim, Norway, 4–8 September 2016, pp. 391–393.

Niderkorn V, Copani G, Martin C, Maxin G, Torrent F, Rochette Y and Ginane C (2019) Effects of including bioactive legumes in grass silage on digestion parameters, nitrogen balance and methane emissions in sheep. *Grass and Forage Science* **74**, 626–635. https://doi.org/10.1111/GFS.12454

Nikola S (1998) Understanding root systems to improve, seedling quality. *HortTechnology*, October – December, **8**, 544–549.

Noorbakhshian SJ, Nabipour M, Meskarbashee M and Amooaghaie R (2011) The effect of pod and priming on germination of sainfoin seed. *Australian Journal of Basic and Applied Sciences* **5**, 800–807.

Noto LV, Cipolla G, Pumo D, and Francipane A (2023) Climate change in the Mediterranean basin (part II): a review of challenges and uncertainties in climate change modeling and impact analyses. *Water Resources Management* **37**, 2307–2323. https://doi.org/10.1007/s11269-023-03444-w

Ojeda-Robertos N, Manolaraki F, Theodoridou K, Aufrere J, Halbwirth H, Stich K, Regos I, Treutter D, Mueller-Harvey I and Hoste H (2010) The anthelmintic effect of sainfoin (silage, hay, fresh) and the role of flavonoid glycosides. *61st Annual Meeting, European Association of Animal Production*, Heraklion, Crete, Greece, pp. 23–27.

O'Mara FP (2012) The role of grasslands in food security and climate change. *Annals of Botany* **110**(6), 1263–1270, https://doi.org/10.1093/aob/mcs209

Özbek H (2011) Sainfoin, *Onobrychis viciifolia* Scop: an important bee plant. *Uludag Aricilik Dergisi Mayis* **11**, 51–62.

Pankov DM (2012) Efficiency of sainfoin cultivation in the forest-steppe of the Altai. *Kormoproizvodstvo (Кормопроизводство)* **10**, 34–36.

Pankov DM (2013) The value of melliferous bees in the rational use of lands. *Feed Production* **10**, 33–35.

Pankov DM (2014) Rating the weed infestation of sainfoin crops from the position of beekeeping. *Feed Production* **1**, 26–32.

Paolini V, Fouraste I and Hoste H (2004) *In vitro* effects of three woody plant and sainfoin extracts on 3rd-stage larvae and adult worms of three gastrointestinal nematodes. *Parasitology* **129**, 69–77. https://doi.org/10.1017/s0031182004005268

Paolini V, Prevot F, Dorchies P and Hoste H (2005) Lack of effects of quebracho and sainfoin hay on incoming third-stage larvae of *Haemonchus* *contortus* in goats. *Veterinary Journal* **170**, 260–263. https://doi.org/10.1016/j.tvjl.2004.05.001

Pareek N (2017) Climate change impact on soils: adaptation and mitigation. *MOJ Ecology & Environmental Sciences* **2**, 136–139. https://doi.org/10.15406/mojes.2017.02.00026

Parker RJ and Moss BR (1981) Nutritional value of Sainfoin hay compared with Alfalfa hay. *Journal of Dairy Science* **64**, 206–210. https://doi.org/10.3168/jds.S0022-0302(81)82555-6

Pathak N and McKinney A (2021) Planetary health, climate change, and lifestyle medicine: threats and opportunities. *American Journal of Lifestyle Medicine* **15**, 541–552. https://doi.org/10.1177/15598276211008127

Pearce AM, O'Neill KM, Miller RS and Blodgett S (2012) Diversity of flower-visiting bees and their pollen loads on a wildflower seed farm in Montana. *Journal of the Kansas Entomological Society* **85**, 97–108. https://doi.org/10.2317/JKES111202.1

Peel MD, Ransom CV and Mott IW (2013) Natural glyphosate tolerance in sainfoin (*Onobrychis viciifolia*). *Crop Science* **53**, 2275–2282. https://doi.org/10.2135/cropsci2012.10.0612

Petersen LK (2019) Impact of climate change on twenty-first century crop yields in the U.S. Climate. **7**, 40. https://doi.org/10.3390/cli7030040

Petrič D, Komáromyová M, Batťányi D, Kozłowska M, Filipiak W, Łukomska A, Ślusarczyk S, Szumacher-Strabel M, Cieślak A, Várady M, Kišidayová S and Váradyová Z (2022) Effect of sainfoin (*Onobrychis viciifolia*) pellets on rumen microbiome and histopathology in lambs exposed to gastrointestinal nematodes. *Agriculture* **12**, 301. https://doi.org/10.3390/agriculture12020301

Phillips BB, Shaw RF, Holland MJ, Fry EL, Bardgett RD, Bullock JM and Osborne JL (2018) Drought reduces floral resources for pollinators. *Global Change Biology* **24**, 3226–3235. https://doi.org/10.1111/gcb.14130

Piper CV (1924) *Forage Plants and Their Culture*. New York: The Macmillan Co.

Porqueddu C, Ledda L and Roggero PP (2000) Role of forage legumes and constraints for forage legume seed production in Mediterranean Europe. *Cahiers Options Méditerranéennes* **45**, 453–460.

Poudel HP, Bhattarai S, Singer SD, Biligetu B and Acharya S (2023) An insight into sainfoin (*Onobrychis viciifolia* Scop.) breeding: challenges and achievements. *Agronomy Journal* **115**, 2843–2858. https://doi.org/10.1002/agj2.21439

Prasad S, Kumar S, Sheetal KR and Venkatramanan V (2020) *Global Climate Change and Biofuels Policy: indian Perspectives*. Singapore: Global Climate Change and Environmental Policy, Springer Singapore, pp. 207–226. https://doi.org/10.1007/978-981-13-9570-36

Prévost D, Bordeleau LM and Antoun H (1987*a*) Symbiotic effectiveness of indigenous arctic rhizobia on a temperate forage legume: sainfoin (*Onobrychis viciifolia*). *Plant and Soil* **104**, 63–69.

Prévost D, Bordeleau LM, Caudry-Reznick S, Schulman HM and Antoun H (1987*b*) Characteristics of rhizobia isolated from three legumes indigenous to the Canadian high arctic: *Astragalus alpinus*, *Oxytropis maydelliana*, and *Oxytropis arctobia*. *Plant and Soil* **98**, 313–324.

Prévost D, Drouin P, Laberge S, Bertrand A, Cloutier J and Lévesque G (2003) Soils and Crops Research and Development Centre, Agriculture and Agri-Food Canada, 2560 Hochelaga Blvd., Sainte-Foy, QC G1V 2J3, Canada.

Provenza FD (1995) Postingestive feedback as an elementary determinant of food preference and intake in ruminants. *Journal of Range Management* **48**, 2–17. http://doi.org/10.2307/4002498

Provorov NA and Tikhonovich IA (2003) Genetic resources for improving nitrogen fixation in legume-rhizobia symbiosis. *Genetic resources and Crop Evolution* **50**, 89–99.

Putnam DH and Orloff SB (2013) Benefits and risks of adapting genetically engineered crops: The Roundup Ready alfalfa story. In: S. Bittman and D. Hunt, editors, Cool forages: Advanced management of temperate forages. Pacific Field Corn Assoc., Agassiz, BC, Canada, pp. 71–76.

Qiao Y, Cheng Q, Zhang Y, Yan W, Yi F and Shi F (2021) Transcriptomic and chemical analyses to identify candidate genes involved in color variation of sainfoin flowers. *BMC Plant Biology* **21**, 1–14. https://doi.org/10.1186/s12870-021-02827-8

Raj S, Roodbar S, Brinkley C and Wolfe DW (2022) Food security and climate change: differences in impacts and adaptation strategies for rural communities in the global south and north. *Frontiers in Sustainable Food Systems* **5**, 691191. https://doi.org/10.3389/fsufs.2021.691191

Ramesh K, Matloob A, Aslam F, Florentine SK and Chauhan BS (2017) Weeds in a changing climate: vulnerabilities, consequences, and implications for future weed management. *Frontiers in Plant Science* **8**, 1–12. https://doi.org/10.3389/fpls.2017.00095

Ran L, Shi H and Yang X (2021) Magnitude and drivers of CO_2 and CH_4 emissions from an arid/semiarid river catchment on the Chinese Loess Plateau. *Journal of Hydrology* **598**, 126260. https://doi.org/10.1016/j.jhydrol.2021.126260

Raza A, Ali HH, Zaheer MS, Iqbal J, Seleiman MF, Sattar J, Ali B, Khan S, Arjumend T and Chauhan BS (2023) Bio-ecology and the management of *Chenopodium murale* L.: A problematic weed in Asia. *Crop Protection* **172**, 106332. https://doi.org/10.1016/j.cropro.2023.106332

Re GA, Piluzza G, Sulas L, Franca A, Porqueddu C, Sanna F and Bullitta S (2014) Condensed tannin accumulation and nitrogen fixation potential of *Onobrychis viciifolia* Scop. grown in a Mediterranean environment. *Journal of the Science of Food and Agriculture* **94**, 639–645. https://doi.org/10.1002/jsfa.6463

Regos I, Urbanella A and Treutter D (2009) Identification and quantification of phenolic compounds from the forage legume sainfoin (*Onobrychis viciifolia*). *Journal of Agricultural and Food Chemistry* **57**, 5843–5852. https://doi.org/10.1021/jf900625r

Ricciardelli D'Albore GC and Roscionii T (1990) Pollinators of sainfoin (*Onobrychis viciifolia*) in a mountain environment. *Apicoltore Moderno* **81**, 195–201.

Richards KW (2019) Effectiveness of the alfalfa leafcutter bee *Megachile rotundata* Fab. to pollinate four perennial legumes. *Journal of Apicultural Research* **59**, 69–76. https://doi.org/10.1080/00218839.2019.1655180

Richards KW and Edwards PD (1988) Density, diversity, and efficiency of pollinators of sainfoin, *Onobrychis viciaefolia* Scop. *The Canadian Entomologist* **120**, 1085–1100. https://doi.org/10.4039/Ent1201085-12

Ríos-De Álvarez L, Greer A, Jackson F, Athanasiadou S, Kyriazakis I and Huntley J (2008) The effect of dietary sainfoin (*Onobrychis viciifolia*) on local cellular responses to Trichostrongylus colubriformis in sheep. *Parasitology* **135**, 1117–1124. https://doi.org/10.1017/S0031182008004563

Rocha J, Oliveira S, Viana CM and Ribeiro AI (2022) Chapter 8 – climate change and its impacts on health, environment and economy. In Prata JC, Ribeiro AI and Rocha-Santos T (eds), *One Health*. Portugal: Academic Press, pp. 253–279. https://doi.org/10.1016/B978-0-12-822794-7.00009-5

Rojas-Downing MM, Nejadhashemi AP, Harrigan T and Woznicki SA (2017) Climate change and livestock: impacts, adaptation, and mitigation. *Climate Risk Management* **16**, 145–163. https://doi.org/10.1016/j.crm.2017.02.001

Rosov SA (1952) Sainfoin – one of the best honey plants in crop rotation. *Pchelovodstvo Mosk* **29**, 46–52.

Rossi LMW, Mao Z, Merino-Martín L, Roumet C, Fort F, Taugourdeau O, Boukcim H, Fourtier S, Del Rey-Granado M, Chevallier T, Cardinael R, Fromin N and Stokes A (2020) Pathways to persistence: plant root traits alter carbon accumulation in different soil carbon pools. *Plant and Soil* **452**, 457–478. https://doi.org/10.1007/s11104-020-04469-5

Roulin A (2014) Melanin-based colour polymorphism responding to climate change. *Global Change Biology* **20**, 3344–3350. https://doi.org/10.1111/gcb.12594

Roy R, Núñez-Delgado A, Wang J, Kader MA, Sarker T, Hasan AK and Dindaroglu T (2021) Cattle manure compost and biochar supplementation improve growth of *Onobrychis viciifolia* in coal-mined spoils under water stress conditions. *Environmental Research* **205**, 112440. https://doi.org/10.1016/j.envres.2021.112440

Rozen JG, Ozebek H, Ascher JS, Sedivy C, Praz C, Monfared A and Mueller A (2010) Nests, petal usages, floral preferences, and immatures of *Osmia* (*Ozbekosmia*) *avosetta* (*Megachilidae*: *Megachilinae*: *Osmiini*), including biological comparisons with other Osmiine bees. *American Museum Novitates* **3680**, 1–22. https://doi.org/10.1206/701.1

Rufino-Moya PJ, Blanco M, Bertolín JR and Joy M (2019) Effect of the method of preservation on the chemical composition and *in vitro* fermentation characteristics in two legumes rich in condensed tannins. *Animal Feed Science and Technology* **251**, 12–20. https://doi.org/10.1016/j.anifeedsci.2019.02.005

Rufino-Moya PJ, Bertolín JR, Blanco M, Lobóna S and Joya M (2022) Fatty acid profile, secondary compounds and antioxidant activities in the fresh forage, hay and silage of sainfoin (*Onobrychis viciifolia*) and sulla (*Hedysarum coronarium*). *Journal of the Science of Food and Agriculture* **102**, 4736–4743. http://doi.org/10.1002/jsfa.11834

Sakhraoui A, Ltaeif HB, Sakhraoui A, Rouz S and Castillo JM (2023) Potential use of wild *Onobrychis* species for climate change mitigation and adaptation. *Crop Science* **63**, 3153–3174. https://doi.org/10.1002/csc2.21088

Salvia M, Olazabal M, Fokaides PA, Tardieu L, Simoes SG, Geneletti D, Huartado S, Viguié V, Spyridaki N, Pietrapertosa F, Ioannou B, Matosovic M, Flamos A, Balzan M, Feliu E, Riznar K, Sel N, Heidrich O and Reckien D (2021) Climate mitigation in the Mediterranean Europe: an assessment of regional and city-level plans. *Journal of Environmental Management* **295**, 113146. https://doi.org/10.1016/j.jenvman.2021.113146

Santos-Medellín C, Liechty Z, Edwards J, Nguyen B, Huang B, Weimer BC and Sundaresan V (2021) Prolonged drought imparts lasting compositional changes to the rice root microbiome. *Nature Plants* **7**, 1065–1077. https://doi.org/10.1038/s41477-021-00967-1

Saratsis A, Regos I, Tzanidakis N, Voutzourakis N, Stefanakis A, Treuter D, Joachim A and Sotiraki S (2012) *In vivo* and *in vitro* efficacy of sainfoin (*Onobrychis viciifolia*) against *Eimeria* spp in lambs. *Veterinary Parasitology* **188**, 1–9.

Sariyildiz T and Savaci G (2020) Ability of green cover from sainfoin (*Onobrychis viciifolia* Scop.) and dog rose (*Rosa canina* L.) to control erosion and improve soil organic carbon and nitrogen stocks in terraces of Northwest Turkey. *Euro-Mediterranean Journal for Environmental Integration* **5**, 9. https://doi.org/10.1007/s41207-020-0148-3

Saunois M, Stavert AR, Poulter B, Bousquet P, Canadell JG, Jackson RB, Raymond PA, Dlugokencky EJ, Houweling S, Patra PK, Ciais PK, Arora P, Bastviken VK, Bergamaschi D, Blake P, Brailsford DR, Bruhwiler G, Carlson L, Carrol KM, Castaldi M, Chandra S, Cevoisier N, Crill C, Covey PM, Curry K, Etiope CL, Frankenberg G, Gedney C, Hegglin N, Höglund-Isaksson MI, Hugelius L, Ishizawa G, Ito M, Janssens-Maenhout A, Jensen G, Joos KM, Kleinen F, Krummel T, Langenfelds PB, Laruelle RL, Liu GG, MachidaL, Maksyutov T, McDonald S, McNorton KC, Miller J, Melton PA, Morino JR, Müller I, Murguia-Flores J, Naik F, Niwa V, Noce Y, O'Doherty S, Parker S, Peng RJ, Peng C, Peters S, Prigent GP, Prinn C, Ramonet R, Regnier M, Riley P, Rosentreter JW, Segers JA, Simpson A, Shi IJ, Smith H, Steele SJ, Thornton LP, Tian BF, Tohjima H, Tubiello Y, Tsuruta FN, Viovy A, Voulgarakis N, Weber A, van Weele TS, van der Werf M, Weiss GR, Worthy RF, Wunch D, Yin D, Yoshida Y, Zhang Y, Zhang W, Zhao Z, Zheng Y, Zhu B, Zhu Q, and Zhuang Q (2020) The global methane budget 2000–2017. *Earth System Science Data* **12**, 1561–1623.

Sayar MS, Han Y and Basbag M (2022) Forage yield and forage quality traits of sainfoin (*Onobrychis viciifolia* Scop.) genotypes and evaluations with biplot analysis. *Fresenius Environmental Bulletin* **31**, 4009–4017.

Scharenberg A, Arrigo Y, Gutzwiller A, Soliva CR, Wyss U, Kreuzer M and Dohme F (2007*a*) Palatability in sheep and *in vitro* nutritional value of dried and ensiled sainfoin (*Onobrychis viciifolia*) birdsfoot trefoil (*Lotus corniculatus*), and chicory (*Cichorium intybus*). *Archives of Animal Nutrition* **61**, 481–496. https://doi.org/10.1080/17450390701664355

Scharenberg A, Arrigo Y, Gutzwiller A, Wyss U, Hess HD, Kreuzer M and Dohme F (2007*b*) Effect of feeding dehydrated and ensiled tanniferous sainfoin (*Onobrychis viciifolia*) on nitrogen and mineral digestion and metabolism of lambs. *Archives of Animal Nutrition* **61**, 390–405.

Scharenberg A, Kreuzer M and Dohme F (2009) Suitability of sainfoin (*Onobrychis viciifolia*) hay as a supplement to fresh grass in dairy cows. *Asian-Australasian Journal of Animal Sciences* **22**, 1005–1015.

Schlautman B, Barriball S, Ciotir C, Herron S and Miller AJ (2018) Perennial grain legume domestication phase I: criteria for candidate Species selection. *Sustainability* **10**, 730. https://doi.org/10.3390/su10030730

Schneiter AA, Whitman WC and Larson KL (1969) Sainfoin. A new legume for North Dakota? *North Dakota Farm Research* **27**, 11–13.

Sears RG, Ditterline RL and Mathre DE (1975) Crown and root rotting organisms affecting sainfoin (*Onobrychis viciaefolia*) in Montana. *Plant Disease Reporter* **59**, 423–426.

Sengul S (2003) Performance of some forage grasses or legumes and their mixtures under dry land conditions. *European Journal of Agronomy* **19**, 401–409. https://doi.org/10.1016/S1161-0301(02)00132-6

Seo SN and Mendelsohn R (2008) An analysis of crop choice: adapting to climate change in South American farms. *Ecological Economics* **67**, 109–116. https://doi.org/10.1016/j.ecolecon.2007.12.007

Sergeeva AG (1955) The effect of lucerne and sainfoin on the water-stable structure of soils under irrigation. *Pocvovedenie* **12**, 35–42.

Sheehy JE and Popple SC (1981) Photosynthesis, water relations, temperature and canopy structure as factors influencing the growth of sainfoin (*Onobrychis viciifolia* Scop.) and lucerne (*Medicago sativa* L.). *Annals of Botany* **48**, 113–128.

Sheldrick R, Thomson D and Newman G (1987) Sainfoin. In Sheldrick RD, Newman G and Roberts DJ. *Legumes for Milk and Meat*. Marlow, UK: Chalcombe Publications, pp. 59–69.

Shen S, Chai X, Zhou Q, Luo D, Wang Y and Liu Z (2019) Development of polymorphic EST-SSR markers and characterization of the autotetraploid genome of sainfoin (*Onobrychis viciifolia*). *PeerJ* **7**, e6542. https://doi.org/10.7717/peerj.6542

Sheppard SC, Cattani DJ, Ominski KH, Biligetu B, Bittman S and McGeough EJ (2019) Sainfoin production in western Canada: a review of agronomic potential and environmental benefits. *Grass and Forage Science* **74**, 6–18. https://doi.org/10.1111/gfs.12403

Simonson WD, Miller E, Jones A, García-Rangel S, Thornton H and McOwen C (2021) Enhancing climate change resilience of ecological restoration – a framework for action. *Perspectives in Ecology and Conservation* **19**, 300–310.

Singh S, Jaiswal DK, Krishna R, Mukherjee A and Verma JP (2019) Restoration of degraded lands through bioenergy plantations. *Restoration Ecology* **28**, 263–266. https://doi.org/10.1111/rec.13095

Skendžić S, Zovko M, Živković IP, Lešić V and Lemić D (2021) The impact of climate change on agricultural insect pests. *Insects* **12**, 440. https://doi.org/10.3390/insects12050440

Slebodnik K, Reeve JR, Norton JM, MacAdam JW and Lee S (2019) Utilization of tannin-containing Forages for sustainable beef production in the Intermountain West. InSSSA International Soils Meeting 7. ASA-CSSA-SSSA.

Slepetys J, Kadziuliene Z, Sarunaite L, Tilvikiene V and Kryzeviciene A (2012) Biomass potential of plants grown for bioenergy production. In *Proceedings of the International Science Conference: Renewable Energy and Energy Efficiency, Growing and Processing Technologies of Energy Crops*, Latvia University of Agriculture, Jelgava, pp. 66–72.

Smoliak S, Jonston A and Hanna M (1972) Germination and seedling growth of alfalfa, sainfoin and cicer milkvetch. *Canadian Journal of Plant Science* **52**, 5.

Smoliński S, Langowska A and Glazaczow A (2021) Raised seasonal temperatures reinforce autumn *Varroa destructor* infestation in honey bee colonies. *Scientific Reports* **11**, 22256. https://doi.org/10.1038/s41598-021-01369-1

Soares D and Rolim J, Fradinho MJ and do Paço TA (2022) Production of preserved forage for horses under water scarcity conditions: a case study. *Water* **14**, 388. https://doi.org/10.3390/w14030388

Sottie ET (2014) *Characterization of New Sainfoin Populations for Mixed Alfalfa Pastures in Western Canada* (PhD thesis). Canada: University of Lethbridge.

Stevovic V, Stanisavljevic R, Djukic D and Djurovic D (2010) Effect of row spacing on seed and forage yield in sainfoin (*Onobrychis viciifolia* Scop.) cultivars. *Tubitak* **36**, 35–45.

Stewart EK, Beauchemin KA, Dai X, MacAdam JW, Christensen RG and Villalba JJ (2019) Effect of tannin-containing hays on enteric methane emissions and nitrogen partitioning in beef cattle. *Journal of Animal Science* **97**, 3286–3299. https://doi.org/10.1093/jas/skz206

Subedi U (2018) *Development of Disease Resistant Fenugreek for Western Canada* (MSc thesis). Canada: Faculty of Art and Science, University of Lethbridge. Available at https://opus.uleth.ca/handle/10133/5179

Sunil S, Akshit R, Sheoran, RS, Satpal S, Harender D, Deepak L, Sushil and K and Paras (2020) Impact of climate change on forage and pasture production and strategies for its mitigation – a review. *Forage Research* **46**, 105–113.

Szalai Z (2001) Development of melliferous plant mixtures with long lasting flowering period. Proceedings of the eight international pollination symposium pollination: integrator of crops and native plant systems. *Acta Horticulturae* **561**, 185–190. https://doi.org/10.17660/ActaHortic.2001.561.27

Taki H, Okabe K, Makino S, Yamaura Y and Sueyoshi M (2009) Contribution of small insects to pollination of common buckwheat, a distylous crop. *Annals of Applied Biology* **155**, 121–129. https://doi.org/10.1111/j.1744-7348.2009.00326.x

Temel S, Keskin B, Şimşek U and Yilmaza İH (2016*a*) The effect of saline and non-saline soil conditions on yield and nutritional characteristics of some perennial legumes forages. *Tarım Bilimleri Dergisi – Journal of Agricultural Sciences* **22**, 528–538. https://doi.org/10.1501/Tarimbil_0000001411

Temel S, Keskin B, Şimşek U and Yilmaza İH (2016*b*) The effect of soils having different salt content on mineral accumulations of some forage legume species. *Fresenius Environmental Bulletin* **25**, 1038–1050.

Terrill TH, Rowan AM, Douglas GB and Barry TN (1992) Determination of extractable and bound condensed tannin concentrations in forage plants, protein concentrate meals and cereal grains. *Journal of the Science of Food and Agriculture* **58**, 321–329. https://doi.org/10.1002/JSFA.2740580306

Terrill TH, Mosjidis J, Moore DA, Shaik SA, Miller D, Burke JM, Muir JP and Wolfe R (2007) Effect of pelleting on efficacy of sericea lespedeza hay as a natural dewormer in goats. *Veterinary Parasitology* **146**, 117–122. https://doi.org/10.1016/j.vetpar.2007.02.005

Theodoridou K, Aufrere J, Andueza D, Pourrat J, Le Morvan A, Stringano E, Mueller-Harvey I and Baumont R (2010) Effects of condensed tannins in fresh sainfoin (*Onobrychis viciifolia*) on *in vivo* and *in situ* digestion in sheep. *Animal Feed Science and Technology* **160**, 23–38. https://doi.org/10.1016/j.anifeedsci.2010.06.007

Theodoridou K, Aufrère J, Niderkorn V, Andueza D, Le Morvan A, Picard F and Baumont R (2011) *In vitro* study of the effects of condensed tannins in sainfoin on the digestive process in the rumen at two vegetation cycles. *Animal Feed Science and Technology* **170**, 147–159. https://doi.org/10.1016/j.anifeedsci.2011.09.003

Thomson JR (1938) The development of sainfoin in its seeding year. *Annals of Applied Biology* **25**, 457–471. https://doi.org/10.1111/j.1744-7348.1938.tb04363.x

Triebwasser DJ, Tharayil N, Preston CM and Gerard PD (2012) The susceptibility of soil enzymes to inhibition by leaf litter tannins is dependent on the tannin chemistry, enzyme class and vegetation history. *New Phytologist* **196**, 1122–1132. https://doi.org/10.1111/j.1469-8137.2012.04346.x

Tufenkci S, Erman M and Sonmez F (2006) Effects of phosphorus and nitrogen applications and *Rhizobium* inoculation on the yield and nutrient uptake of sainfoin (*Onobrychis viciifolia* L.) under irrigated conditions in Turkey. *New Zealand Journal of Agricultural Research* **49**, 101–105. https://doi.org/10.1080/00288233.2006.9513699

Turk M and Celik N (2006) The effects of different row spaces and seeding rates on the hay and crude protein yields of Sainfoin (*Onobrychis sativa* Lam.). *Journal of Agricultural Sciences* **12**, 175–181. https://doi.org/10.1501/Tarimbil_0000000470

Turk M, Albayrak S, Tuzun CG and Yuksel O (2011) Effects of fertilisation and harvesting stages on forage yield and quality of sainfoin (*Onobrychis viciifolia* Scop.). *Bulgarian Journal of Agricultural Science* **17**, 789–794.

Ülger İ and Kaplan M (2016) Variations in potential nutritive value, gas and methane production of local Sainfoin (*Onobrychis sativa*) Populations. *Alınteri Zirai Bilimler Dergisi* **31**, 42–47.

USDA (2005) *Animal and Plant Health Inspection Service. Biotechnology Regulatory Service*. United States: Department of Agriculture, p. 8.

USDA SARE (2007) *Managing Cover Crops Profitably*, 3rd Edn. United States: USDA SARE, p. 244. Available at http://www.sare.org/publications/covercrops/buckwheat.shtml

Uzun S, Avci S, Ozcan S and Sancak C (2017) Effects of NaCl on germination and seedling characteristics of different *Onobrychis* taxa. *Fresenius Environmental Bulletin* **26**, 6317–6323.

Vallero DA (2019) *Air Pollution Calculations. Chapter 8 – Air Pollution Biogeochemistry*. Elsevier, pp. 175–206. https://doi.org/10.1016/B978-0-12-814934-8.00008-9

van der Geest K, van der Geest K, de Sherbinin A, Kienberger S, Zommers Z, Sitati A, Roberts E and James R (2019) The impacts of climate change on ecosystem services and resulting losses and damages to people and society. In Mechler R, Bouwer L, Schinko T, Surminski S and Linnerooth-Bayer J (eds), *Loss and Damage from Climate Change. Climate Risk Management, Policy and Governance*. Cham: Springer, pp. 221–236. https://doi.org/10.1007/978-3-319-72026-5_9

Vasta V, Yáñez-Ruiz DR, Mele M, Serra A, Luciano G, Lanza M, Biondi L and Priolo A (2010) Bacterial and protozoal communities and fatty acid profile in the rumen of sheep fed a diet containing added tannins. *Applied and Environmental Microbiology* **76**, 2549–2555.

Vereshchagin AL, Nickolay BV and Alexandra NA (2015) Identification du miel du territoire de l'altai par calorimétrie différentielle à balayage et analyse thermomecanique. **1**, 107–111.

Villalba JJ and Provenza FD (1997) Preference for flavoured foods by lambs conditioned with intraruminal administration of nitrogen. *British Journal of Nutrition* **78**, 545–561. https://doi.org/10.1079/bjn19970174

Villalba JJ and Provenza FD (2000) Postingestive feedback from starch influences the ingestive behaviour of sheep consuming wheat straw. *Applied Animal Behaviour Science* **66**, 49–63. https://doi.org/10.1016/S0168-1591(99)00081-7

Villalba JJ, Provenza FD and Stott R (2009) Rumen distension and contraction influence feed preference by sheep. *Journal of Animal Science* **87**, 340–350. https://doi.org/10.2527/jas.2008-1109

Villalba JJ, Miller J, Hall JO, Clemensen AK, Stott R, Snyder D and Provenza FD (2013) Preference for tanniferous (*Onobrychis viciifolia*) and non-tanniferous (*Astragalus cicer*) forage plants by sheep in response to challenge infection with *Haemonchus contortus. Small Ruminant Research* **112**, 199–207. https://doi.org/10.1016/j.smallrumres.2012.11.033

Villalba JJ, Ates S and MacAdam JW (2021) Non-fiber carbohydrates in forages and their influence on beef production systems. *Frontiers in Sustainable Food Systems* **5**, 566338. https://doi.org/10.3389/fsufs.2021.566338

Waghorn G (2008) Beneficial and detrimental effects of dietary condensed tannins for sustainable sheep and goat production – progress and challenges. *Animal Feed Science and Technology* **147**, 116–139. http://doi.org/10.1016/j.anifeedsci.2007.09.013

Waghorn GC, Jones WT, Shelton ID and McNabb WC (1990) Condensed tannins and the nutritive value of herbage. *Proceedings of the New Zealand Grassland Association* **51**, 171–176. https://doi.org/10.33584/jnzg.1990.51.1894

Waghorn GC, Douglas GB, Niezen JH, McNabb WC and Foote AG (1998) Forages with condensed tannins – their management and nutritive value for ruminants. *Proceedings of the New Zealand Grassland Association* **60**, 89–98.

Wallace LE (1968) Current and Potential Insect Problems of Sainfoin in America. Sainfoin Symposium. Montana: Montana Agriculture Experimental Station Bulletin.

Wang Y, Berg BP, Barbieri LR, Veira DM and McAllister TA (2006) Comparison of alfalfa and mixed alfalfa-sainfoin pastures for grazing cattle: effects on incidence of bloat, ruminal fermentation, and feed intake. *Canadian Journal of Animal Science* **86**, 383–392. https://doi.org/10.4141/A06-009

Wang Y, Barbieri LR, Berg BP and McAllister TA (2007) Effects of mixing sainfoin with alfalfa on ensiling, ruminal fermentation and total tract digestion of silage. *Animal Feed Science and Technology* **135**, 296–314. https://doi.org/10.1016/j.anifeedsci.2006.07.002

Wang Y, Mcallister TA and Acharya S (2015) Condensed tannins in sainfoin: composition, concentration, and effects on nutritive and feeding value of sainfoin forage. *Crop Science* **55**, 13–22.

Wang Q, Li F, Zhang D, Liu Q, Li G, Liu X, Li X and Chen J (2018) Sediment control and fodder yield increase in alfalfa (*Medicago sativa* L) production with tied-ridge-furrow rainwater harvesting on sloping land. *Field Crops Research* **225**, 55–63. http://doi.org/10.1016/j.fcr.2018.05.017

Wang M, Chen M, Bai J, Zhang J, Su R, Franco M, Ding Z, Zhang X, Zhang Y and Guo X (2022) Ensiling characteristics, *in vitro* rumen fermentation profile, methane emission and archaeal and protozoal community of silage prepared with alfalfa, sainfoin and their mixture. *Animal Feed Science and Technology* **284**, 115154. https://doi.org/10.1016/j.anifeedsci.2021.115154

Warner D, Bannink A, Hatew B, Van Laar H and Dijkstra J (2017) Effects of grass silage quality and level of feed intake on enteric methane production in lactating dairy cows. *Journal of Animal Science* **95**, 3687–3699. https://doi.org/10.2527/jas2017.1459

Wei J, Peng L, He Z, Lu Y and Wang F (2020) Potential distribution of two invasive pineapple pests under climate change. *Pest Management Science* **76**, 1652–1663. https://doi.org/10.1002/ps.5684

Weiwei LU, Xinxiao YU, Guodong JIA, Hanzhi LI and Ziqiang LIU (2018) Responses of intrinsic water-use efficiency and tree growth to climate change in semi-arid areas of North China. *Scientific Reports* **8**, 308. https://doi.org/10.1038/s41598-017-18694-z

Westphal C, Bommarco R, Lamborn E, Petanidou T, Potts SG, Roberts SPM, Szentgyörgyi H, Vaissière BE, Woyciechowski M and Steffan-Dewenter I (2008) Measuring bee biodiversity in different habitats and biogeographic regions. *Ecological Monographs* **78**, 653–671. https://doi.org/10.1890/07-1292.1

Wiesner L, Carleton A and Cooper C (1968) Factors affecting sainfoin seed germination and emergence. Sainfoin Symposium. Montana Agriculture Experimental Station Bulletin. Bozeman, MT: Montana State University.

Wijekoon C, Acharya SN, Siow YL, Sura S, Thandapilly S and Sabra A (2021) Canadian sainfoin and fenugreek as forage and functional foods. *Crop Science* **61**, 1–20. https://doi.org/10.1002/csc2.20280

Wilkins RJ and Jones R (2000) Alternative home-grown protein sources for ruminants in the United Kingdom. *Animal Feed Science and Technology* **85**, 23–32. https://doi.org/10.1016/S0377-8401(00)00140-1

Williams SRO, Moatea PJ, Hannaha MC, Ribauxa BE, Wales WJ and Eckard RJ (2011) Background matters with the SF6 tracer method for estimating enteric methane emissions from dairy cows: A critical evaluation of the SF6 procedure. *Animal Feed Science and Technology* **170**, 265–276.

Wood TJ, Michez D, Paxton RJ, Drossart M, Neumann P, Gérard M, Vanderplanck M, Barraud A, Martinet B, Leclercq N and Vereecken NJ (2020) Managed honey bees as a radar for wild bee decline? *Apidologie* **51**, 1100–1116. https://doi.org/10.1007/s13592-020-00788-9

Wu GQ, Feng RJ, Li SJ and Du YY (2017*a*) Exogenous application of proline alleviates salt-induced toxicity in sainfoin seedlings. *Journal of Animal and Plant Sciences* **27**, 246–251.

Wu GL, Feng RH, Wang C and Du Y (2017*b*) Silicon ameliorates the adverse effects of salt stress on sainfoin (*Onobrychis viciaefolia*) seedlings. *Plant, Soil and Environment* **63**, 545–551. https://doi.org/10.17221/665/2017-PSE

Wu Y, Zhao F, Liu S, Wang L, Qiu L, Alexandrov G and Jothiprakash V (2018) Bioenergy production and environmental impacts. *Geoscience Letters* **5**, 14. https://doi.org/10.1186/s40562-018-0114-y

Wu GQ, Li H, Zhu YH and Li SJ (2021) Comparative physiological response of sainfoin (*Onobrychis viciaefolia*) seedlings to alkaline and saline-alkaline stress. *The Journal of Animal and Plant Sciences* **31**, 1028–1035. https://doi.org/10.36899/JAPS.2021.4.0299

Xu BC, Gichuki P, Shan L and Li FM (2006) Aboveground biomass production and soil water dynamics of four leguminous forages in semiarid region, northwest China. *South African Journal of Botany* **72**, 507–516.

Yakovlev GP, Sytin AK and Roskov YUR (1996) *Legumes of Northern Eurasia, a Check-List*. Kew: Royal Botanic Gardens.

Yakupoglu T, Gundogan R, Dindaroglu T, Kusvuran K, Gokmen V, Rodrigo-Comino J, Gyasi-Agyei Y and Cerdà A (2021) Tillage impacts on initial soil erosion in wheat and sainfoin fields under simulated extreme rainfall treatments. *Sustainability* **13**, 789. https://doi.org/10.3390/su13020789

Yin H, Zhou H, Wang W, Tran L-SP and Zhang B (2020) Transcriptome analysis reveals potential roles of abscisic acid and polyphenols in adaptation of *Onobrychis viciifolia* to extreme environmental conditions in the Qinghai-Tibetan plateau. *Biomolecules* **10**, 967. https://doi.org/10.3390/biom10060967

Yin H, Zhou H, Wang W, *et al.* (2021) Evidence for miRNAs involved in the high-altitude responses of sainfoin (*Onobrychis viciifolia*) grown in the Qinghai-Tibetan plateau. *Journal of Plant Biochemistry and Biotechnology* **31**, 533–544. https://doi.org/10.1007/s13562-021-00702-z

Yousef MAZ and Abdul-Karim S (2012) Ecological studies on nitrogen fixing bacteria from leguminous plants at the north of Jordan. *African Journal of Microbiology Research* **6**, 3656–3661. http://doi.org/10.5897/AJMR12.098

Yu Y, Wei W, Chen LD, Jia FY, Yang L, Zhang HD and Feng TJ (2015) Responses of vertical soil moisture to rainfall pulses and land uses in a typical loess hilly area, China. *Solid Earth* **6**, 595–608. https://doi.org/10.5194/se-6-595-2015

Yüksek F and Yüksek T (2015) Growth performance of Sainfoin and its effects on the runoff, soil loss and sediment concentration in a semi-arid region of Turkey. *CATENA* **133**, 309–317. https://doi.org/10.1016/j.catena.2015.05.018

Zandalinas SI, Balfagon D, Gomez-Cadenas A and Mittler R (2022) Responses of plants to climate change: metabolic changes during abiotic stress combination in plants. *Journal of Experimental Botany* **73**, 3339–3354. https://doi.org/10.1093/jxb/erac073

Zhang H, Pan C, Gu S, Ma Q, Zhang Y, Li X and Shi K (2019*a*) Stomatal movements are involved in elevated CO_2-mitigated high temperature stress in tomato. *Physiologia Plantarum* **165**, 569–583. https://doi.org/10.1111/ppl.12752

Zhang D, Wang Q, Li G, Li X and Sample DJ (2019*b*) Optimum ridge width and suitable mulching material for sainfoin production with ridge-furrow rainwater harvesting in semiarid regions of China. *Arid Land Research and Management* **33**, 274–296. https://doi.org/10.1080/15324982.2018.1563241

Zhang GS, Clair AL, Dolezal AG, Toth AL and O'Neal ME (2022) Can native plants mitigate climate-related forage dearth for honey bees (*Hymenoptera*: *Apidae*)? *Journal of Economic Entomology* **115**, 1–9. https://doi.org/10.1093/jee/toab202

Zinyengere N, Crespo O and Hachigonta S (2013) Crop response to climate change in southern Africa: a comprehensive review. *Global and Planetary Change* **111**, 118–126. https://doi.org/10.1016/j.gloplacha.2013.08.010

Zörb C, Geilfus CM and Dietz KJ (2019) Salinity and crop yield. *Plant Biology* **21**, 1–38. https://doi.org/10.1111/plb.12884