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A review of significance of allelopathy in anticipating negative climate change effects

Introduction

Climate change is commonly used in context with the phenomenon of rising global temperatures and altering weather patterns and is recognised as a pressing issue with far-reaching implications for ecosystems, biodiversity, and human well-being (Urban, 2015; Malhi et al., 2020; Abbas et al., 2022; Shivanna, 2022). Extensive research has been conducted to understand the causes and effects of climate change, particularly in the agricultural sector (Pautasso et al., 2012; Thornton, Lipper, 2014; Ortiz et al., 2021). However, there is a lesser-known ecological phenomenon called allelopathy that deserves attention for its crucial role in shaping the impacts of climate change. Allelopathy is the phenomenon in which plants release biochemical compounds into their environment, affecting the growth and development of other organisms (Barabasz-Krasny et al., 2023). These compounds, known as allelochemicals, can have various effects ranging from inhibiting the growth of competing species to deterring herbivores or pathogens (Cheng, Cheng, 2015). Allelopathy plays a significant role in shaping the structure and composition of ecosystems by influencing plant interactions and community dynamics (Anaya, 1999; Inderjit et al., 2011).

Climate change has a direct impact on allelopathy as it alters environmental conditions for plant growth such as temperature, rainfall patterns, and carbon dioxide (CO_2) concentrations (Dalgleish et al., 2010; Bae et al., 2019). These changes can affect the production and release of allelochemicals, leading to shifts in the competitive balance among plants (entry of alien species). For example, increased temperatures may enhance the production of allelochemicals by some alien plant species, allowing them to outcompete others and dominate the ecosystem (Gaofeng et al., 2018; Felpeto et al., 2019). Changes in precipitation patterns can have a significant impact on various plant physio-ecological processes (Barker et al., 2006; Shi et al., 2022). Consequently, these changes directly affect the biosynthesis, leaching, and diffusion of allelochemicals, altering both their availability and effectiveness in terms of inhibiting other species (Scavo et al., 2019; Singh et al., 2021).

Moreover, it is worth noting that allelopathy can be indirectly influenced by climate change through the distribution and abundance of plants (Bertran et al., 2011). As temperatures rise, some plant species may shift their ranges to cooler regions, while others may become more dominant in their current habitats (Telwala et al., 2013). These changes can influence the abundance and diversity of allelochemicals in different ecosystems, potentially leading to cascading effects on plant communities and overall ecosystem functioning (Loreau et al., 2001; Nogués-Bravo et al., 2007; Locatelli et al., 2008; Lv, 2009; Gao et al., 2022).

The implications of allelopathy in the context of climate change are significant. Understanding the mechanisms and effects of allelopathy can help predict and mitigate the impacts of climate change on ecosystems (Xu et al., 2023). By considering the allelopathic interactions between plant species, conservation efforts can be designed to promote biodiversity and resilience in the face of changing climatic conditions (Altieri et al., 2015). Incorporating allelopathic effects into ecological models and management plans can improve the accuracy and effectiveness of restoration efforts, ensuring the long-term sustainability of ecosystems (Hierro, Callaway, 2021). While climate changes are fully accepted as a challenge to ecosystems and human well-being, the role of allelopathy in the same context is often overlooked. The phenomenon of allelopathy, wherein plants release biochemical compounds that affect other organisms, interacts intricately with climate change (Kostina-Bednarz et al., 2023). Understanding the mechanisms and implications of allelopathy is a challenge for improving ecosystem management and conservation strategies. A focus on allelopathic interactions and their consequences bear a so far not well recognised option for mitigating the effects of climate change and foster sustainable ecosystems for future generations (Choudhary et al., 2023). This review aims to delve into the concept of allelopathy, explore its mechanisms, discuss its significance for managing the effects of climate change, and examine its implications for ecosystems and restoration efforts.

Allelopathy and climate change

Climate change has the potential to alter allelopathic interactions in several ways (Felpeto et al., 2019). Firstly, rising temperatures and changing precipitation patterns can affect the production, release and availability of allelochemicals (Singh et al., 2021). A study by Appiah et al. (2022) revealed that temperature and precipitation variations influence the concentration of carnosic acid in rosemary leaves, with the highest and lowest concentrations reported for September (high temperature) and February (low rainfall). Moreover, an increased amount of carnosic acid was detected during the summer with high rainfall and temperature (Lemos et al., 2015). Increased temperatures may enhance the synthesis and release of these compounds, leading to stronger allelopathic effects on nearby plants (Gaofeng et al., 2018; Felpeto et al., 2019; Canton et al., 2021). However, there are few reports showing a reduction in the concentration of allelochemicals after a rise in temperature (Munné-Bosch, Alegre, 2000; Luis, Johnson, 2005). Changes in rainfall patterns can also influence the leaching and transport of allelochemicals, affecting their availability and impact on neighbouring plants (Jamieson et al., 2013). This can be observed in concentration variations of the allelochemical collected from the rosemary leaf samples in a seasonal sampling in Tunisia (Appiah et al., 2022). Seasonal variation in the allelopathic activity of *Artemisia monosperma* Delile extracts was observed, with samples collected during autumn and summer exhibiting greater potential against the weed *Dactyloctenium aegyptium* (L.) Wild. and the crop *Lactuca sativa* L. compared to samples collected during other seasons (Abd-ElGawad et al., 2023). In addition to changes in chemical production and availability, climate change-induced shifts in plant communities can also alter allelopathic interactions (Zhang et al., 2021). As certain species become more dominant or invasive due to changing environmental conditions, their allelopathic effects may intensify, leading to reduced biodiversity and altered overall ecosystem dynamics and functioning (Rai et al., 2020). Earlier studies conducted on the mechanisms and impacts of cogongrass (*Imperata cylindrica* (L.) P. Beauv.) invasions in various regions, including the United States, have consistently demonstrated its adverse effect on the diversity and composition of native ecological communities and ecosystems (Pyšek et al., 2012; Powell et al., 2013; Estrada, Flory, 2015). Conversely, some plants may lose their allelopathic capabilities under changing climatic conditions, potentially affecting their competitive advantage and survival (Wang et al., 2022a). Overall, climate change has the potential to significantly impact allelopathic interactions among plants (Tredennick et al., 2016). Changes in temperature, precipitation patterns, and plant communities can all influence the production, availability, and effectiveness of allelochemicals (Scavo et al., 2019). These alterations can have profound effects on biodiversity, ecosystem dynamics, and the overall structure and functioning of ecosystems (Ridenour, Callaway, 2001). The intricate connections between climate change and allelopathy highlight the importance of considering these factors in conservation and restoration strategies for our precious ecosystems.

Allelopathic potential in the face of rising atmospheric CO_2

Global mean atmospheric CO_2 levels have experienced a significant increase by a third since preindustrial times, and it is projected to further rise to a range of 600 to 1000 ppm by the year 2100 (*IPCC*, 2014). This increase in CO_2 concentration is predominantly responsible for climate change and has far-reaching consequences for terrestrial biology (Wang et al., 2010). Consequently, there has been a particular focus on comprehending the implications of rising atmospheric CO_2 levels on the distribution, growth, and pollen production of invasive exotic species, owing to the inherent risks they pose to native ecosystems and public health (Bae et al., 2019). Typically, elevated levels of atmospheric CO_2 increase the supply of carbon to plants, resulting in higher carbon-to-nitrogen ratios in their tissues. This shift in ratios creates favourable conditions for the production of carbon-based secondary compounds (Bazin et al. 2002; Coviella et al. 2002; Räisänen, et al. 2008). More specifically, in their studies, Bae et al. (2019), demonstrated that Common ragweed (*Ambrosia artemisiifolia* L. var. *elatior*), as the most well-known invaded species, has the potential to enhance its growth parameters and increase the relative concentrations of allelochemicals including major monoterpenes (DL-limonene 105%, β-myrcene 203%, and 1,3,6-Octatriene 258%) and sesquiterpenes (germacrene-D 138%, β-caryophyllene 421%) in association with CO_2 elevation.

It's widely known that allelochemicals play a crucial role in influencing the invasiveness of plants by enhancing their competitiveness and overall fitness (Barabasz-Krasny et al., 2023). This, in turn, determines their global ecological boundaries (Applebee et al., 1999; Bae et al., 2019). Additionally, these compounds have the potential to facilitate the successful establishment and proliferation of both native and exotic plants within their respective local or introduced/invaded ranges (Callaway, Ridenour, 2004; Xu et al., 2006; Wang et al., 2010; Zandi et al., 2020). Given the intrinsic advantage of invasive species in competing for environmental resources (Barabasz-Krasny et al., 2023), a raise in atmospheric CO_2 levels could potentially amplify their dominance over native species. This amplification may result in an expansion of their territorial reach, thereby posing a significant threat to native ecosystems and the preservation of natural biodiversity (Choi et al., 2011; Lehoczky et al., 2011). For instance, the uncontrolled proliferation of invasive species like *Impatiens parviflora* (Small balsam), *Impatiens glandulifera* Royle (Himalayan balsam), *Solidago gigantea* Aiton (Early Goldenrod), *Reynoutria japonica* Houtt. (Japanese knotweed), and *Robinia pseudoacacia* L. (Black locust) (Bomanowska et al., 2019) within protected areas of Poland, due to climate change associated with CO_2 elevation, may even become an inevitable occurrence.

Elevated temperature and allelopathy: cascading effects on plant communities, biodiversity, and ecosystem

Climate warming, mainly caused by greenhouse gas emissions, considerably endangers the growth, development, and productivity of diverse plant species (*IPCC*, 2021). The consequences are observed through notable changes in temperature and precipitation patterns, which deeply impact the ability of plants to thrive and reproduce (Reidsma et al., 2009; Lobell, Gourdji, 2012; Abbass et al., 2022). Consequently, climate change disrupts the crucial temperature ranges necessary for the survival of species, posing a significant risk to their overall viability and existence. This perturbation additionally disrupts the chemical response of plants and triggers alterations in the ecological function of plant allelochemicals, which are crucial compounds governing their interactions with other organisms in the environment (Harvey, Malcicka, 2015). As a result, this disruption intensifies the rapid loss of biodiversity and deeply influences the structural dynamics of ecosystems, presenting significant challenges to the sustainability of our planet (*IPCC*, 2021).

In a study conducted by Allemann et al. (2017), the relationship between allelochemicals and temperature as an environmental factor was extensively examined. The results of their study demonstrated that an increase in temperature significantly enhanced the allelopathic function of *Amaranthus cruentus* L., leading to the inhibition of germination and growth in pepper (*Capsicum annuum* L.), tomato (*Solanum lycopersicum* L.), and lettuce (*Lactuca sativa*). This study emphasised the significant impact of temperature on allelopathy and the need to consider environmental factors in crop management.

Climate change has consequences that extend beyond direct temperature effects. Changes in temperature regimes can disrupt species interactions and ecological relationships, including allelopathy. When the environment shifts, it can alter the timing and intensity of allelopathic interactions between plants, which in turn affects the growth and survival of neighbouring organisms (Ridenour, Callaway, 2001). These changes in allelopathic processes can contribute to shifts in plant community composition and biodiversity dynamics (Bais et al., 2004).

Allelopathic potential under altered precipitation patterns

One of the consequences of climate change is altered precipitation patterns (*IPCC*, 2021; Bhowmik, 2022). As the climate warms, different regions experience changes in rainfall and snowfall patterns, including the frequency, intensity, and distribution of precipitation events (*IPCC*, 2021). Changes in rainfall patterns can disrupt the water cycle, affecting the availability and distribution of freshwater resources (*IPCC*, 2021). This, in turn, can have implications for agriculture, wildlife habitats, and human settlements that rely on consistent water supplies (*IPCC*, 2019). The impact of altered precipitation extends beyond water availability. It can also contribute to changes in ecosystems and biodiversity (*IPBES*, 2019). Some species may struggle to adapt to shifts in precipitation patterns, leading to changes in species distribution, migration patterns, and even extinctions (*IPBES*, 2019). Additionally, changes in precipitation can profoundly influence plant growth and development (*IPCC*, 2021). Variations in rainfall patterns may alter the timing of flowering and fruiting, impacting the reproductive cycles of plant species (*IPBES*, 2019). Moreover, changes in precipitation can affect the dynamics of plant competition and interactions with other organisms, ultimately modifying ecosystem composition and functioning (*IPBES*, 2019). The seasonal evaluation of rosemary (*Rosmarinus officinalis* L.) leaf extracts suggests that the concentration of carnosic acids was lower during summer with high temperature and low precipitation rates (Munné-Bosch, Alegre, 2000; Luis, Johnson, 2005). However, contradictory results were observed in rosemary plants exposed to similar summer conditions in Tunisian. In this case, the inhibitory effects of rosemary leaf samples were actually the highest, attributed to the presence of a high concentration of carnosic acids (Appiah et al., 2022). It is suggested that the inverse relationship between carnosic acid concentration and precipitation could be explained by the process of leaching, where precipitation interacts with the rosemary leave extracts, causing the carnosic acids to be washed away or diluted. Therefore, changes in rainfall patterns may affect plant exudation and leaching of allelochemicals into the soil (Jamieson et al., 2013). In other words, altered precipitation can impact the growth and biomass production of plants, ultimately affecting the availability and release of allelochemicals (Gobbo-Neto, Lopes, 2007; Gatti et al., 2012). Under increased precipitation or extended rainy periods, plants may increase their root exudation, leading to higher levels of allelochemicals released into the soil solution or nearby water bodies (Diller et al., 2023). The release of allelopathic substances becomes particularly significant when densely-growing allelopathic plants are exposed to increased rainfall, leading to a significant impact on aquatic ecosystems, especially during the rainy season (Kisielius et al., 2020). For example, pyrrolizidine alkaloids (PA) originating from plants such as *Senecio jacobaea* L. or *Petasites hybridus* (L.) G. Gaertn., B. Mey. & Scherb. have been identified at concentrations of up to 90 ng/l in small streams, and concentrations of up to 230 ng/l in seepage water during rainfall events (Kisielius et al., 2020). Furthermore, initial studies indicate the presence of a specific allelopathic compound called 2-methoxy-1,4-naphthoquinone (2-MNQ), which can be released from leaves and potentially reach concentrations as high as 12 mg/l in rainfall runoff (Lobstein et al., 2001; Ruckli et al., 2014). The presence of 2-MNQ exerts an impact on the growth and development of neighbouring plants, such as *Urtica dioica* L., by significantly reducing shoot and root growth (Gruntman, et al., 2014; Ruckli et al., 2014; Bieberich et al., 2018). It can be observed from the above information that the increased release of allelopathic substances intensifies the allelopathic effects of these plants, potentially inhibiting the growth of neighbouring plants and influencing community dynamics.

As mentioned before, environmental factors like climate (e.g., precipitation rates) play a role in the concentration of allelopathic substances in plants (Maqbool, Abdul, 2013). To our knowledge, there is currently insufficient evidence regarding the impact of reduced precipitation or prolonged drought on the overall allelopathic potential of invasive and indigenous species. Although a limited number of studies have proposed that plants tend to limit the release of allelochemicals under unfavourable water-limited conditions (Didyk et al., 2021; Hashoum et al., 2021), the prevailing majority of research emphasises the positive correlation between drought stress and intensification of allelopathy in invasive species (Motamedi et al., 2016; Rositska, 2020; Wu et al., 2012). Aimed to estimate the differences in the allelopathy between invasive woody species (*Rhus typhina* L.) and indigenous woody species (*Sapindus mukorossi* Gaerten) under drought stress, Zhong et al. (2023) demonstrated that drought stress reinforced the allelopathy of both the invasive (>14.59%) and indigenous (>54.17%) species.

When rainfall is scarce or during prolonged drought periods, it is commonly observed that plants tend to produce allelochemicals, specifically phenolic acids and terpenoids (Kostina-Bednarz et al., 2023). In dry soil conditions, certain plant species like sunflower (*Tithonia diversifolia* (Hemsl.) A. Gray), sorghum (*Sorghum bicolor* (L.) Moench), walnut (*Cyperus rotundus* L.), cassava (*Manihot esculenta* Crantz), and wheat (*Triticum* sp.) have been found to exhibit increased levels of cyanogenic glycosides (Maqbool, Abdul, 2013). Similarly, prolonged drought can lead to higher concentrations of ferulic acid in wheat and momilactones A and B in rice (Maqbool, Abdul, 2013; Scavo, Mauromicale, 2021). However, it is important to note that the impact of altered precipitation on allelopathic potential can vary depending on specific plant species and environmental conditions (Gaofeng et al., 2018; Motmainna et al., 2023). Therefore, further academic research is essential to comprehensively understand the intricate relationship between climate-induced changes in precipitation, allelopathy, and plant interactions.

Allelopathy: an overlooked factor among the impacts of climate change on ecosystems

Until now allelopathy is not high up in the list of factors considered having significance for modulating the consequences a changing climate for ecosystems (Cheng, Cheng, 2015; *IPCC*, 2021). However, understanding the implications of allelopathy has potential for developing effective ecosystem restoration and conservation strategies (Kostina-Bednarz et al., 2023).

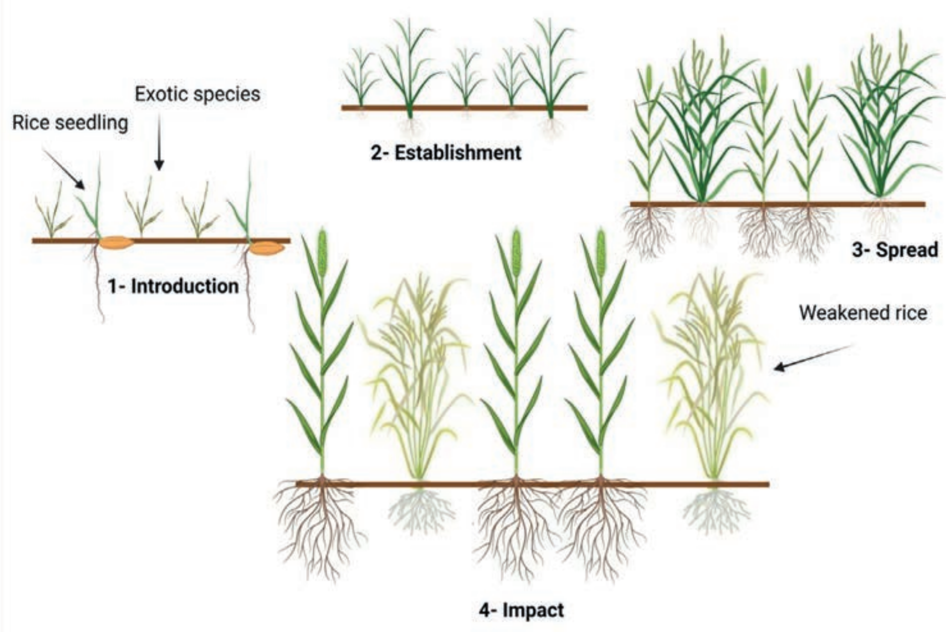

Fig. 1. Conceptual model of the plant invasion process (Conceptual model by P. Zandi)

Impact on native vegetation and biodiversity

The presence of invasive plant species with strong allelopathic characteristics poses a significant threat to native vegetation (Zhong et al., 2023). These invaders often possess competitive advantages such as rapid growth rates, extensive resource acquisition, and effective defence mechanisms, allowing them to outcompete indigenous plants in their habitat (Fig. 1) (Zenni et al., 2016; Barabasz-Krasny et al., 2023). The displacement and suppression of native vegetation by invasive species can lead to a decline in biodiversity within affected ecosystems (Alldred et al., 2016). Native plants often have specialised relationships with local pollinators, herbivores, and other organisms, forming complex ecological networks (Barabasz-Krasny et al., 2023). The introduction and dominance of allelopathic invasive species disrupt these intricate interactions, leading to the loss of specialised plant-animal relationships and reducing overall species diversity (Pyšek et al, 2010; Rai, Singh, 2020). The decline in biodiversity caused by invasive species has profound implications for ecosystem functionality and stability. Native species are adapted to local environmental conditions, and the loss of these adapted species undermines the capacity of ecosystems to perform important ecological functions. Ecosystem stability relies on the presence of diverse vegetation as it enhances resilience to disturbances, promotes nutrient cycling, soil formation, and facilitates the provision of ecosystem services (Wang et al., 2022a). Moreover, invasive species can alter ecosystem processes and functions by modifying soil properties and nutrient dynamics. High allelopathic invasive plants may release chemicals into the soil that inhibit the growth and establishment of native plants, thus further exacerbating their competitive advantage. This disruption in plant community composition and nutrient cycling can have cascading effects on trophic interactions and ecosystem processes (Rai, Singh, 2020).

The protection and restoration of native vegetation play a pivotal role in mitigating the adverse impacts of invasive species on biodiversity and ecosystem functionality (Loreau et al., 2001; Alldred et al., 2016). By implementing effective management strategies, such as early detection, rapid response, and comprehensive control measures against invasive species, it become feasible to avert the displacement of native vegetation and foster the resilience of ecosystems (Wang et al., 2022a). Empirical studies conducted in the submontane forests of Hawaiian Volcanoes National Park have demonstrated the marked benefits of persistent removal of non-native perennial grasses over a span of four years (D'Antonio et al., 1999). While this practice evidently resulted in heightened local shrub growth and recruitment of woody species within the forest ecosystem, it is highly recommended to thoroughly consider the associated costs of preserving or eradicating invasive species, particularly in multi-functional ecosystems (Tilman, 1999; Kremen et al., 2005). Alldred et al. (2016) undertook a scientific inquiry focused on the removal of invasive *Phragmites australis* (Cav.) Trin. ex Steud. from tidal freshwater marshes in the Hudson River. Their study highlighted the vital importance of achieving a delicate balance between conserving the diversity of native plants, notably *Typha angustifolia* L., and sustaining nitrogen removal services in wetland ecosystems through controlled removal of invasive alien species.

To mitigate climate change's adverse impact on ecosystems, especially in forest-rich developing nations, a crucial approach is large-scale ecological restoration through the reintroduction of native plant species and the establishment of habitat corridors (Cao et al., 2011; De Groot et al., 2013). This approach facilitates biodiversity recovery and the restoration of vital ecological functions (Loreau et al., 2001; Bustamante et al., 2019). Brazil's climate action plan serves as a notable example, setting a target to restore and reforest 12 million hectares of forests for diverse objectives by 2030 (Harris et al., 2006; Fengler et al., 2017; Simonson et al., 2021). However, restoring ecosystems in tropical and mega-diverse countries comes with significant challenges, encompassing technical and financial feasibility, policy development, monitoring mechanisms, and integration with climate change strategies and other sectors (Bustamante et al., 2019). The effectiveness of restoration programs depends on tailored planning, execution, and monitoring, taking into account reference ecosystems like forests, savannas, grasslands, and wetlands (Simonson et al., 2021). Insufficient integration of national and subnational climate policies, as well as other sectoral policies, hinders the broad-scale implementation of restoration initiatives. The Brazilian case highlights the possibility of reducing deforestation but emphasises the necessity for enhanced national commitment and international support to drive transformative actions in the forest sector (Fengler et al., 2017; Bustamante et al., 2019).

Influences on soil health, fertility and erosion

There's mounting evidence indicating that plant-soil interactions are pivotal in facilitating the successful invasion of alien species and driving plant-plant interactions (Steinlein, 2013; Qu et al., 2021). It is well-established that soil microbial communities play a vital role in the processes of soil nutrient cycling and soil health (Chodak et al., 2015). Additionally, they prevent soil erosion by forming stable aggregates (binding soil particles), improving soil structure and stability and enhancing plant root growth (Chalkos et al., 2021; Wang et al., 2022b; Hartmann, Six, 2023). Invasive alien plant species can outcompete and displace native species by employing allelopathy, which involves direct and/ or indirect (e.g., microbial functioning) changing of soil conditions (e.g. soil stability, soil attributes) through underground root exudates (Callaway et al., 2000). This can lead to soil erosion (or limited topsoil fertility) (Pejchar, Mooney, 2009) and a reduction in native plant diversity (Lazzaro et al., 2014) (Fig. 2).

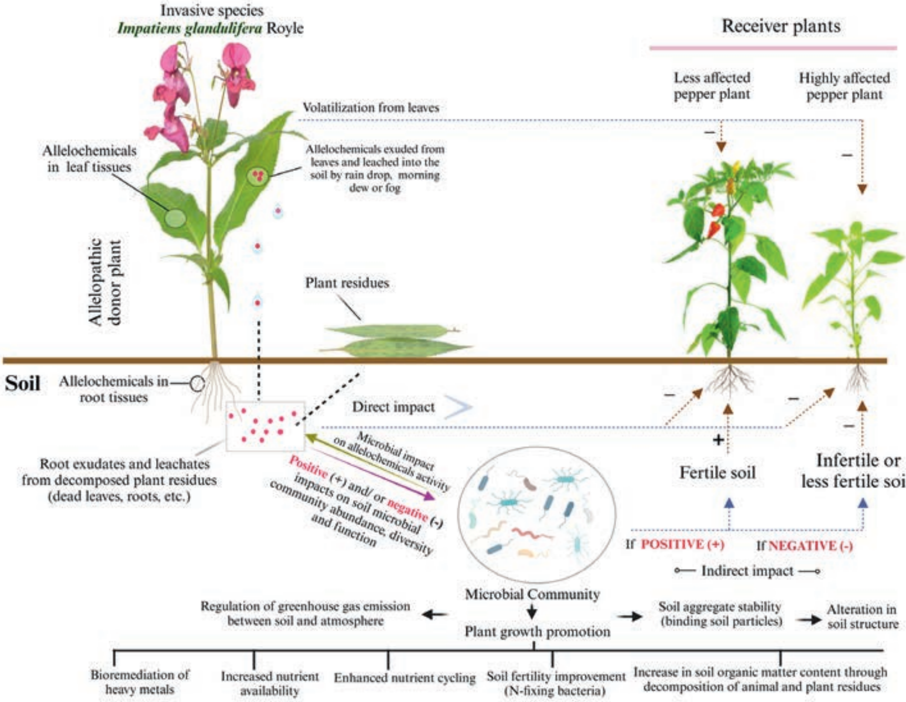

Fig. 2. Schematic illustration on the concept of soil erosion (or limited topsoil fertility) under the influence of allelopathic-driven soil microbial activity (Schematic illustration by P. Zandi)

The invasion of noxious invasive alien plant species such as spotted knapweed (*Centaurea stoebe* L.), cheat grass (*Bromus tectorum* L.), and leafy spurge (*Euphorbia esula* L.) had a profound impact on the soil quality of grassland ecosystems (Gibbons et al., 2017) Specifically, the presence of *Acacia dealbata* Link, a common invasive species in Mediterranean ecosystems, has been shown to disrupt soil chemistry and microbial functioning, resulting in reduced native plant diversity (Lazzaro et al., 2014). These allelochemicals have been found to influence the composition, structure and abundance of soil microbial communities or inhibit and/or stimulate their growth and activity, thereby indirectly inducing alterations in soil properties (Haichar et al., 2008; Broeckling et al., 2008; Fan et al., 2010; Xiao et al., 2019; Li et al., 2020; Qu et al., 2021) and fertility (Wang et al., 2022b). Consequently, this disruption in the soil environment suppresses the nutrient uptake of native plants, ultimately hindering their normal growth processes (Steinlein, 2013; Rutgers et al., 2016). Root exudates from *Allium sativum* L. have been observed to inhibit the growth of the mycelium and germination of zoospores of *Phytophthora capsici* Leonian (Muhammad et al., 2011). In a recent study conducted by Qu et al. (2021), it was demonstrated that root extracts of *R. typhina* have the potential to inhibit the growth of cultivated plants (*Tagetes erecta* L.) and soil microbial activity. This suggests that the allelochemicals present in *R. typhina* roots may have an influence on plant-microbe interactions. Additionally, another study by Cheng et al. (2022) found that allelochemicals released from the root of *Stellera chamaejasme* L. can affect the composition and diversity of the rhizosphere soil microbial community. These findings further support the notion that allelochemicals play a role in shaping the microbial dynamics in soil. It is important to note that soil microbes have the ability to convert allelopathic compounds into non-allelopathic substances (Fig. 2) (Inderjit, 2005), thus reducing the allelopathic effect of invaded plants (Li et al., 2017) and potentially impacting plant-to-plant interactions (Ehlers, 2011).

Allelopathic interactions, known for their ability to impede the growth of adjacent plants via the emission of chemical substances (Mohammadkhani, Servati, 2018; Zandi et al., 2019, 2020; Khamare et al., 2022), have been proposed as influential catalysts contributing to the escalation of soil erosion by disrupting soil health and fertility (Fig. 2) (Pejchar, Mooney, 2009; Inderjit et al., 2011). The absence of ground vegetation in eucalyptus woodlands strongly suggests the allelopathic influence of eucalyptus on the environment, hindering the development of other plant species (e.g., *Acmena acuminatissima* (Blume) Merr. & L.M. Perry, *Cryptocarya concinna* Hance, and *Pterospermum lanceaefolium* Roxb. ex DC.) as well as inducing soil degradation (Zhang, Fu, 2009; Chu et al., 2014; Puig et al. 2018). Despite the scarcity of information regarding the secretion of allelochemicals from roots and their implications for soil fertility, investigations into the recognition of microbes involved in soil nutrient availability and their activities in invaded soils (Wang et al., 2022b) offer a promising avenue for understanding the potential influence of allelochemicals on soil erosion. Addressing the hypothesis of allelopathy-driven soil erosion (Fig. 2) is crucial for sustainable land management and ecosystem conservation (Lalljee et al., 2000; Chu et al., 2014). Strategies such as promoting diverse plant species composition, incorporating erosion control measures, and managing land use practices can help mitigate the negative effects of allelopathic interactions on soil erosion (Ain et al., 2023).

Disrupted nutrient cycling and their availability

Invasive plants, known for their aggressive growth and domination of ecosystems, exert a significant influence on nutrient cycling processes (Zhang et al., 2009; Zhu et al., 2020). This impact varies based on multiple factors, including the specific invasive plant species, initial soil nutrient levels (Dassonville et al., 2008; Slesak et al., 2016), nutrient status of the invasive plants themselves (Vanderhoeven et al., 2006), and the decomposition rate of their litter (Arthur et al., 2012). The release of allelopathic compounds by these invasive species usually disrupts the delicate balance of nutrient dynamics within ecosystems, resulting in disturbances to nutrient cycling patterns (Scavo et al., 2019; Afzal et al., 2023).

It has been suggested that the allelopathic substance, depending on its concentration (Cesco et al., 2012), has a significant impact on soil properties, such as soil acidity (pH) and nutrient availability (White, 1994; Zhu et al., 2020). It is worth noting that soil pH can directly or indirectly impact factors such as the availability of soil nutrient elements, soil microbial composition, enzyme activity, and the metabolism of allelochemicals (Staddon et al., 1998; Kobayashi, 2004). Zhang et al. (2009) and more recently, Zhu et al. (2020), have both shown that higher concentrations of allelopathic substances derived from invasive species, *Solidago canadensis* L. and *Stellera chamaejasme*, respectively, can cause an increase in soil pH. Explicitly, Zhu et al. (2020) have attributed the inhibitory effect of *S. chamaejasme* root exudates on the growth of *Leymus chinensis* (Trin.) Tzvelev, a perennial grass, to the elevated concentration of these exudates. Their research uncovered a strong correlation between higher soil acidity levels and a decrease in soil available nitrogen (AN), available phosphorus (AP), total phosphorus (TP), and total nitrogen (TN) levels (Zhu et al., 2020). This finding suggests that higher pH values, which disrupt nutrient availability, further worsen the adverse impact of allelochemicals on targeted plants. Similar reductions in soil TN and TP levels were also observed within the rhizosphere soil of *S. chamaejasme* in studies conducted by Sun et al. (2009) and He et al. (2019).

As mentioned earlier, allelopathic compounds released by invasive plants can inhibit the activity of soil microorganisms responsible for nutrient decomposition and mineralisation (Lorenzo et al., 2013). These compounds can impede the enzymatic activities of soil microbes, affecting their ability to break down organic matter and release nutrients for plant uptake (Cheng et al., 2022). As a result, nutrient availability is compromised, limiting the growth and development of native vegetation (Fig. 2). Additionally, the allelopathic effects of invasive plants can alter the composition and diversity of soil microbial communities (Kourtev et al., 2003; Lankau, 2011). Certain allelochemicals may selectively inhibit the growth of specific microbial species, resulting in imbalances within the microbial community structure. This disruption can further compromise nutrient cycling efficiency, as different microbial groups play essential roles in nutrient transformations and cycling processes. The disruption of nutrient cycling caused by invasive plant allelopathy has far-reaching implications for ecosystem productivity and resilience, particularly in the face of climate change stressors. Reduced nutrient availability can limit the growth and vigour of native plant species, making them more susceptible to environmental stressors such as drought or elevated temperatures. This, in turn, can lead to decreased ecosystem productivity and reduced ability to adapt to changing environmental conditions.

To address the challenge of disrupted nutrient cycling, management strategies should aim to control invasive plant species and restore native plant communities (Cao et al., 2011; Kostina-Bednarz et al., 2023). South Africa for instance is a country which took early measures to protect its native ecosystems (Jubase et al., 2021). Managed removal of invasive species can help alleviate the allelopathic pressure on native plants and promote the recovery of nutrient cycling processes (Alldred et al., 2016). In addition, implementing practices that enhance soil fertility and promote beneficial soil microorganisms can contribute to improving nutrient availability and cycling efficiency in ecosystems.

Conclusion

Allelopathy, the chemical interaction between plants, plays a significant role in shaping the impacts of climate change on ecosystems. Changes in temperature, precipitation patterns, and plant community composition can influence the strength and direction of allelopathic effects. Recognising the importance of allelopathy in the context of climate change is essential for understanding and managing the complex ecological dynamics that arise from these interactions. By integrating allelopathy into conservation and restoration practices, we can enhance our ability to mitigate the effects of climate change and promote resilient ecosystems. Continued research, collaboration, and practical application of allelopathic knowledge are needed to develop effective strategies for sustainable ecosystem management in a changing world.

Conflict of interest

The authors declare no conflict of interest related to this article.

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Przegląd znaczenia allelopatii w przewidywaniu negatywnych skutków zmian klimatycznych

Streszczenie

Allelopatia dotyczy interakcji chemicznych między roślinami, podczas których niektóre gatunki uwalniają substancje chemiczne, które wpływają na wzrost, rozwój i przeżycie sąsiednich roślin. Chemikalia te, zwane allelochemikaliami, mogą mieć również pozytywne lub negatywne skutki uboczne dla całych ekosystemów. Zjawisko allelopatii może oddziaływać na ekosystem w połączeniu ze zmianami klimatycznymi. Jednakże powszechne zrozumienie ekologicznych implikacji allelopatii i jej wpływu na dynamikę zbiorowisk roślinnych, skład gatunkowy i różnorodność biologiczną nadal jest ograniczone. Znaczenie allelopatii dla wpływu zmian klimatu na rolnictwo wiąże się z jej interakcją z sekwestracją węgla, obiegiem składników odżywczych i stanem gleby, a także z emisją gazów cieplarnianych. W niniejszym przeglądzie podkreślono znaczenie allelopatii jako istotnego procesu ekologicznego dla zrównoważonego zarządzania gruntami oraz odporności ekosystemów w obliczu wyzwań związanych z klimatem.

Słowa kluczowe: allelochemikalia, zmiana klimatu, odporność ekosystemów, gatunki inwazyjne, zrównoważone, gospodarowanie gruntami

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