

Impacts of *Ambrosia psilostachya* Invasion on Soil Properties and Microbial Communities in Caspian Coastal Ecosystems

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Abstract

Invasive alien plants can profoundly reshape soil properties and microbial communities, thereby disrupting key ecosystem processes. We investigated the impact of *Ambrosia psilostachya* invasion on soil physicochemical and biological characteristics in Guilan Province, Southwest Asia. Soil samples were collected from invaded and non-invaded sites across three contrasting locations: Anzali Free Zone (AFZ), Anzali Town (AT), and Anzali Beach (AB). We measured soil pH, electrical conductivity (EC), nutrient concentrations, organic matter, organic carbon, microbial biomass, and respiration.

Across all sites, invasion by *A. psilostachya* consistently reduced soil pH while increasing EC. Nitrogen (N), phosphorus (P), and potassium (K) concentrations were generally enhanced, although P showed no significant change at AFZ and AB. Invaded soils also exhibited higher organic carbon, organic matter, and microbial biomass carbon. Microbial activity was markedly stimulated, as indicated by increased basal respiration (BR), substrate-induced respiration (SIR), and respiratory quotient (qCO_2).

Overall, our findings demonstrate that *A. psilostachya* substantially modifies soil chemical and biological processes, creating conditions that may reinforce its establishment and competitive dominance. These insights highlight the role of soil–plant–microbe interactions in the success of invasive weeds and underscore the need for their consideration in management strategies.

Introduction

Biological invasions are a global concern, as they can significantly alter the structure and function of recipient ecosystems (Ricciardi et al., 2017; Wekhanya, 2016). Invasive plant species often disrupt soil physicochemical and biological properties, affecting nutrient cycling and key ecosystem processes (Broadbent et al., 2017; Castro-Díez & Alonso, 2017; Fraterrigo et al., 2011; Knapp et al., 2012; Lavoie, 2017; Pathak et al., 2019; Rodríguez-Caballero et al., 2017). These alterations can lead to positive feedback loops that reinforce invasion success and hinder the recovery of native plant communities (Stefanowicz et al., 2016, 2019).

Ambrosia psilostachya (western ragweed, Asteraceae), native to North America, has spread to several parts of the world and is now considered an invasive species, especially in coastal areas (Fried et al., 2015; Montagnani et al., 2017; Vecchio et al., 2015). Traits contributing to its invasiveness include vegetative propagation via rhizomes (Bassett & Crompton, 1975), high seed production (4.5 to 536 seeds m^{-2}) (Fumanal et al., 2008), mycorrhizal colonization even in polluted environments (Busby et al., 2011; Rivera-Becerril et al., 2013), and allelopathic interactions (Dalrymple & Rogers, 1983). The species is classified as a noxious weed in degraded rangelands in the United States and is listed as a quarantine pest in Russia (Afonin et al., 2008; Gillen et al., 1991). In Iran, *Ambrosia* spp. were first reported in 1991 in Bandar-e Anzali (Guilan Province) (Mozaffarian, 1991), and subsequent taxonomic confirmation identified the species as *A. psilostachya* (Tokasi et al., 2018).

Although numerous studies have addressed the effects of plant invasions on soil biota and chemistry, data on the impact of *Ambrosia* species—particularly *A. psilostachya*—on soil characteristics remain scarce. For instance, Qin et al. (2014) reported increased microbial abundance and nutrient availability in soils invaded by *A. artemisiifolia*. Similarly, Comole et al. (2021) found higher macronutrient concentrations and organic matter under *Prosopis velutina* invasion. Such changes may enhance invader-soil feedbacks, further increasing plant competitiveness. However, other studies have shown reductions in soil nutrient levels under invasive species (Christian & Wilson, 1999; Leary et al., 2006), indicating that invasion effects are context-dependent and influenced by factors such as plant species identity, site characteristics, and seasonality (Herr et al., 2007; Pyšek et al., 2012; Comole et al., 2021).

Soil microbial biomass (SMB), a key indicator of soil biological activity, directly influences plant diversity, productivity, and community stability (Raiesi & Beheshti, 2015). Microbial respiration, typically assessed via basal respiration (BR) and substrate-induced respiration (SIR), reflects microbial functional responses to soil conditions (ISO 17155, 2002; Zak et al., 2008). The respiratory quotient (qCO_2) serves as an indicator of microbial metabolic efficiency (Yang et al., 2010). Invasive species such as *Solidago canadensis* have been shown to enhance microbial biomass, respiration, and carbon source utilization, while reducing qCO_2 , suggesting a shift toward more efficient microbial communities (Min et al., 2011).

To date, no studies have investigated the impact of *A. psilostachya* on soil properties in the Guilan region of Iran. Therefore, the aim of this study was to evaluate the effects of *A. psilostachya* invasion on soil physicochemical properties, nutrient concentrations, microbial biomass, and microbial respiration. We hypothesized that the occurrence of *A. psilostachya* significantly alters soil chemical and biological characteristics, potentially facilitating its persistence and expansion in invaded habitats.

Materials and methods

Study site

This study was conducted in the coastal region of Guilan Province, northern Iran (37.4639° N, 49.4799° E), where clonal populations of *Ambrosia psilostachya* are established (Fig. 1). The area is characterized by a temperate, humid coastal climate, with average annual air temperatures ranging from 13°C to 19°C and annual precipitation between 1200 and 1800 mm. Monthly mean minimum and maximum temperatures are 7°C and 26°C, respectively. Anzali Port experiences approximately 148 rainy days per year, with March having the highest number of rainy days (15.5 days on average) and July the lowest (6 days on average).

Three sites were selected for sampling: Anzali Free Zone (AFZ), Anzali Town (AT), and Anzali Beach (AB). At each site, two adjacent areas were identified: one invaded by *A. psilostachya* (85–95% plant cover) and a nearby non-invaded area (0% *A. psilostachya* cover), located 50 to 100 meters apart. All sampling plots were at comparable elevation and slope to minimize variation due to topography (Fig. 1).

Soil sampling and measurement

At the end of summer 2020, five soil samples were randomly collected from each experimental plot. After removing surface litter, the top 0–20 cm layer of soil was sampled using a 5-cm diameter soil corer. Each sample was homogenized, air-dried, and passed through a 2 mm sieve. The processed soil was then divided into two subsamples: one portion was air-dried at room temperature for physical and chemical analyses, while the second portion was stored at 4°C for microbial respiration and microbial biomass measurements.

Soil physical and chemical analyses

Soil texture (sand, silt, and clay fractions) was determined using the hydrometer method (Bashour & Sayegh, 2007). Soil pH was measured in a 1:2.5 (w/v) suspension of soil and distilled water using a digital pH meter (pH Rex-2, Lei-Ci, Shanghai). Electrical conductivity (EC) was determined using the saturated paste extract method (Khorsandi & Yazdi, 2011).

Total nitrogen (N) was measured using the Kjeldahl method (Bremner & Mulvaney, 1982). Available phosphorus (P) was analyzed using the molybdenum blue colorimetric method (Olsen, 1954), while total potassium (K) was determined via flame atomic absorption spectrophotometry (Z-5300, Polarized Zeeman AAS) according to Sparks et al. (1996). Soil organic carbon (SOC) was quantified following the Walkley–Black method (Walkley & Black, 1934).

Microbial biomass carbon (MBC) was calculated using the fumigation-extraction method as:

$$\text{MBC } (\mu\text{g C g}^{-1}) = (\text{CF} - \text{CUF}) / \text{KEC},$$

where CF is the organic C in fumigated soil, CUF is the organic C in non-fumigated soil, and KEC (0.35) is the extraction efficiency coefficient (Joergensen et al., 1995; Wu et al., 1990).

Enumeration of total culturable bacteria

To estimate culturable bacterial abundance, 1 g of fresh soil was suspended in 9 ml of sterile distilled water to prepare a 1:10 dilution. The suspension was homogenized for 30 minutes. A serial dilution was performed, and aliquots were plated on nutrient agar. Plates were incubated at 25–30°C for up to 10 days, after which colony-forming units (CFU) were counted to estimate bacterial density.

Soil respiration assays

Basal respiration (BR) was measured using the sodium hydroxide (NaOH) trap method (Alef, 1995). Substrate-induced respiration (SIR) followed the same procedure as BR, with the addition of glucose as

an energy source (Anderson & Domsch, 1978). The respiratory quotient (qCO_2) was calculated as the ratio of BR to microbial biomass carbon (BR/MBC), following Anderson & Domsch (1990).

Data analysis

All data were statistically analyzed using the PROC GLM procedure in SAS software (version 9.1; SAS Institute Inc., Cary, NC, USA). Prior to analysis, data were tested for homogeneity of variance. One-way analysis of variance (ANOVA) was used to assess the effects of site and invasion status on soil variables. Means were compared using Duncan's multiple range test at a significance level of $P \leq 0.05$.

Results

Effect of soil texture on *Ambrosia psilostachya* invasion

In general, *A. psilostachya* invasion was less pronounced in soils with higher sand content (Fig. 2a). At the AFZ and AT sites, the sand percentage in invaded soils was 5.00% and 12.89% lower, respectively, compared to non-invaded soils. However, no significant difference in sand content was observed between invaded and non-invaded soils at the AB site.

Conversely, *A. psilostachya* invasion tended to occur more frequently in soils with higher silt content at the AFZ and AT sites (Fig. 2b). The most pronounced difference was observed at AT, where the silt percentage in invaded soil was 33.34% higher than in non-invaded soil. At the AB site, no significant difference in silt content was detected between invaded and non-invaded soils.

Regarding clay content, a significant difference was found only at the AT site, where invaded soil had 39.28% more clay compared to the non-invaded counterpart. No significant variation in clay content was observed between invaded and non-invaded soils at the AFZ and AB sites.

Effect of *Ambrosia psilostachya* invasion on soil electrical conductivity (EC) and pH

Soil pH and electrical conductivity (EC) were significantly affected by *A. psilostachya* invasion (Fig. 3a–b). At the AFZ and AB sites, soil pH was significantly lower in invaded areas compared to non-invaded ones. In contrast, no significant difference in pH was observed between invaded and non-invaded soils at the AT site.

Soil EC increased in response to *A. psilostachya* invasion at the AT and AB sites, with the highest EC values recorded in invaded soils at the AT site (Fig. 3b). However, at the AFZ site, the difference in EC between invaded and non-invaded soils was not statistically significant.

Effect of *Ambrosia psilostachya* invasion on soil nitrogen, phosphorus, and potassium concentrations

Ambrosia psilostachya invasion significantly influenced soil nutrient concentrations across all study sites (Fig. 4). Nitrogen (N) levels were consistently higher in invaded soils compared to non-invaded counterparts. Specifically, N concentrations increased by 63%, 44%, and 82% at the AFZ, AT, and AB sites, respectively.

Phosphorus (P) concentrations showed a variable response to invasion. No significant differences were observed between invaded and non-invaded soils at the AFZ and AB sites. In fact, P levels were undetectable in both invaded and non-invaded soils at AFZ, and in the non-invaded soil at AB. However, a marked increase in P concentration was recorded in invaded soils at the AT site, where P levels were, on average, 79% higher than in the non-invaded area.

Potassium (K) concentrations were significantly higher in invaded soils at all three sites (Fig. 4). The highest K levels were observed at the AT site, while the lowest were recorded at AFZ. Invasion by *A. psilostachya* resulted in a slight increase in K concentration at AFZ and AB, whereas a pronounced increase was found at AT.

Effect of *Ambrosia psilostachya* invasion on soil microbial properties

Soil organic carbon (SOC) and soil organic matter (SOM) were significantly affected by the presence of *A. psilostachya* (Fig. 5). In all three study sites, invaded soils exhibited higher SOC and SOM levels compared to non-invaded areas. At the AT site, in particular, *A. psilostachya* invasion resulted in an approximate two-fold increase in both SOC and SOM compared to the non-invaded site.

The highest microbial biomass carbon (MBC) was recorded in invaded soils at the AT site. MBC values at this location were 64% and 69% higher than those measured at the invaded sites of AFZ and AB, respectively. Significant differences in MBC between invaded and non-invaded soils were observed at AFZ and AT. However, no significant difference in MBC was detected between invaded and non-invaded soils at the AB site.

These findings suggest that *A. psilostachya* invasion enhances microbial biomass and organic matter accumulation, potentially creating more favorable conditions for its persistence.

Effect of *Ambrosia psilostachya* invasion on total bacterial abundance and microbial respiration

Total bacterial abundance was significantly affected by *A. psilostachya* invasion (Fig. 6a). In the AFZ and AB sites, the number of culturable bacteria was significantly higher in invaded soils compared to non-

invaded areas. In contrast, at the AT site, invasion by *A. psilostachya* led to a 6.27% decrease in total bacterial counts in the rhizosphere.

Soil basal respiration (BR) and substrate-induced respiration (SIR) were also significantly influenced by the presence of *A. psilostachya*. Across all three sites, invaded soils exhibited consistently higher BR and SIR values than non-invaded soils, with the highest values recorded at the AT site (Fig. 6b–c). These results indicate an increase in microbial metabolic activity in the presence of the invasive species.

The respiratory quotient (qCO_2) was also elevated in invaded soils at the AFZ and AB sites, where values were 75.75% and 48.86% higher, respectively, than those in non-invaded soils (Fig. 6d). However, no significant difference in qCO_2 was detected at the AT site.

These changes in bacterial abundance and respiratory activity suggest that *A. psilostachya* modifies microbial processes, potentially reinforcing its establishment in the invaded habitats.

Discussion

This study provides the first comprehensive evaluation of the impacts of *Ambrosia psilostachya* invasion on soil physicochemical and microbial properties. Our findings show that *A. psilostachya* preferentially colonizes soils with higher silt and clay content, particularly at the AFZ and AT sites, while sandy soils were more commonly associated with non-invaded areas. This suggests a potential link between soil texture and invasion success.

Similar observations were reported for *A. artemisiifolia*, which also prefers finer-textured soils (Bassett & Crompton, 1975). Other studies support this pattern, showing that clay-rich soils enhance the growth of invasive species such as *Physalis angulata* and *P. philadelphica* due to improved water and nutrient retention (Ozaslan et al., 2016). In contrast, some weed species like *Avena fatua* and *Galium aparine* have been shown to prefer sandy loam soils (Gulshan & Dasti, 2006). Soil texture strongly influences plant distribution by affecting moisture availability, nutrient retention, and root penetration—factors critical for the establishment and competitiveness of invasive species.

Soil pH, a key factor influencing nutrient bioavailability and microbial activity, was significantly reduced in areas invaded by *A. psilostachya*, particularly at the AFZ and AB sites. These findings align with previous reports where invasive species altered soil pH (Ruwanza & Dondofema, 2020; Tererai et al., 2015). The pH values observed (6.95–7.47) indicate that *A. psilostachya* thrives in neutral to slightly alkaline soils—conditions that also favor microbial activity and nutrient cycling (Brady et al., 2010; Wang et al., 2012).

In contrast to pH, electrical conductivity (EC) was significantly higher in invaded soils at the AT and AB sites. Elevated EC may reflect higher nutrient concentrations resulting from the accumulation of organic matter under invasive plant canopies (Kassa et al., 2010). These changes suggest that *A. psilostachya* modifies the soil environment in ways that may reinforce its persistence and expansion.

Invasion by *A. psilostachya* also led to marked increases in macronutrient concentrations (N, P, and K), with the exception of P in the AFZ and AB sites. Enhanced nutrient availability has been widely reported in soils invaded by other species, such as *A. artemisiifolia* (Qin et al., 2014) and *Halogeton glomeratus* (Duda et al., 2003). However, other studies have reported neutral or even negative impacts on soil nutrients (Stanek et al., 2020), indicating that effects are species- and context-dependent. Nitrogen enrichment, in particular, is known to promote the biomass of invasive species while suppressing native flora (Jones & Chapman, 2011; Wang et al., 2015).

The increased potassium content in invaded soils, especially at the AT site, may enhance plant resistance to stress factors such as herbivory, cold, and waterlogging (Sardans & Peñuelas, 2015). This is likely facilitated by *A. psilostachya*'s deep and extensive root system (up to 1.83 m), which enhances nutrient uptake and gives it a competitive advantage (Stromberg, 2013; Vermeire et al., 2005).

Our results also demonstrated that invasion significantly increased soil organic carbon and organic matter across all sites. This is consistent with findings from *Carpobrotus edulis* invasion, where higher SOM was observed in invaded soils (Conser & Connor, 2009). Organic matter is critical for sustaining microbial communities and nutrient cycling, and its increase may further promote conditions favorable to invasion.

Soil microbial biomass carbon (MBC) was significantly higher in invaded soils at the AFZ and AT sites, indicating an overall enhancement of microbial abundance. This could be due to shifts in the composition and activity of microbial communities beneath *A. psilostachya*, which in turn influence nutrient immobilization and retention.

Soil respiration parameters (BR, SIR, and qCO_2) were also elevated in invaded sites, suggesting increased microbial activity and metabolic intensity. Similar results have been reported under other invasive species such as *Lantana camara* (Fan et al., 2010). The increased respiration may be attributed to enhanced nutrient and organic matter availability, which stimulates microbial decomposition and carbon turnover (Chander & Brookes, 1991; Leita et al., 1999; Emmerling et al., 2000). Higher qCO_2 indicates increased microbial stress or energy expenditure, often linked to rapid microbial turnover under nutrient-rich conditions (Cheng et al., 1996).

Overall, *A. psilostachya* invasion significantly altered soil physicochemical properties, increasing nutrient concentrations, organic carbon, microbial biomass, and respiration activity. Among the three study sites, the AT site exhibited the most pronounced changes, suggesting site-specific interactions between soil characteristics and invasion dynamics.

These findings highlight the potential of *A. psilostachya* to modify soil ecosystems in ways that reinforce its own invasion success. Its ability to alter soil structure, nutrient dynamics, and microbial activity suggests a strong feedback loop that facilitates its establishment and spread. Soils with higher clay and silt content appear particularly susceptible, indicating that soil texture could serve as a predictive factor for future invasion risk.

Conclusions

This study represents the first in-depth investigation of the effects of *Ambrosia psilostachya* invasion on soil physicochemical and microbial properties in the Guilan coastal region of Iran. Our findings reveal that *A. psilostachya* not only alters soil texture preferences, favoring silt- and clay-rich substrates, but also drives significant increases in soil nutrient content, organic carbon, microbial biomass, and respiration rates. These changes suggest the presence of a strong plant–soil feedback loop that may reinforce the species' invasive success.

For weed ecologists, soil microbiologists, and land management professionals, this work provides novel insights into the belowground mechanisms facilitating the establishment and dominance of an aggressive invader. Unlike many previous studies that focus solely on aboveground impacts, our research highlights the critical, and often overlooked, role of soil processes in invasion ecology—an angle that remains underrepresented in the current literature.

Looking forward, future research should focus on long-term monitoring of *A. psilostachya* invasions under different land-use and climatic conditions, as well as experimental manipulations to disentangle causality in plant–soil–microbe interactions. Assessing the impact of this species on native plant recruitment and soil food webs will also be crucial. Such integrative approaches will not only deepen our understanding of invasion dynamics but also inform more effective, soil-based management strategies for limiting the spread of invasive weeds.

Declarations

Data availability statement:

All data are contained in the text, further data will be made available upon reasonable request to the corresponding author.

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Conflict of interest disclosure:

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Ethics approval statement:

NA

Patient consent statement:

NA

Permission to reproduce material from other sources:

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Clinical trial registration:

NA

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by **Hesan Saberi**, **Majid Pouryousef**, **Somayeh Tokasi** and **Sakineh Rashidi**. The first draft of the manuscript was written by **Ali Reza Yousefi** and **Andrea Mastinu** and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Figures



Figure 1

Study sites location in Bandar anzali (Anzali port), Iran, Anzali free zone (AFZ), Anzali town (AT), and Anzali beach (AB).

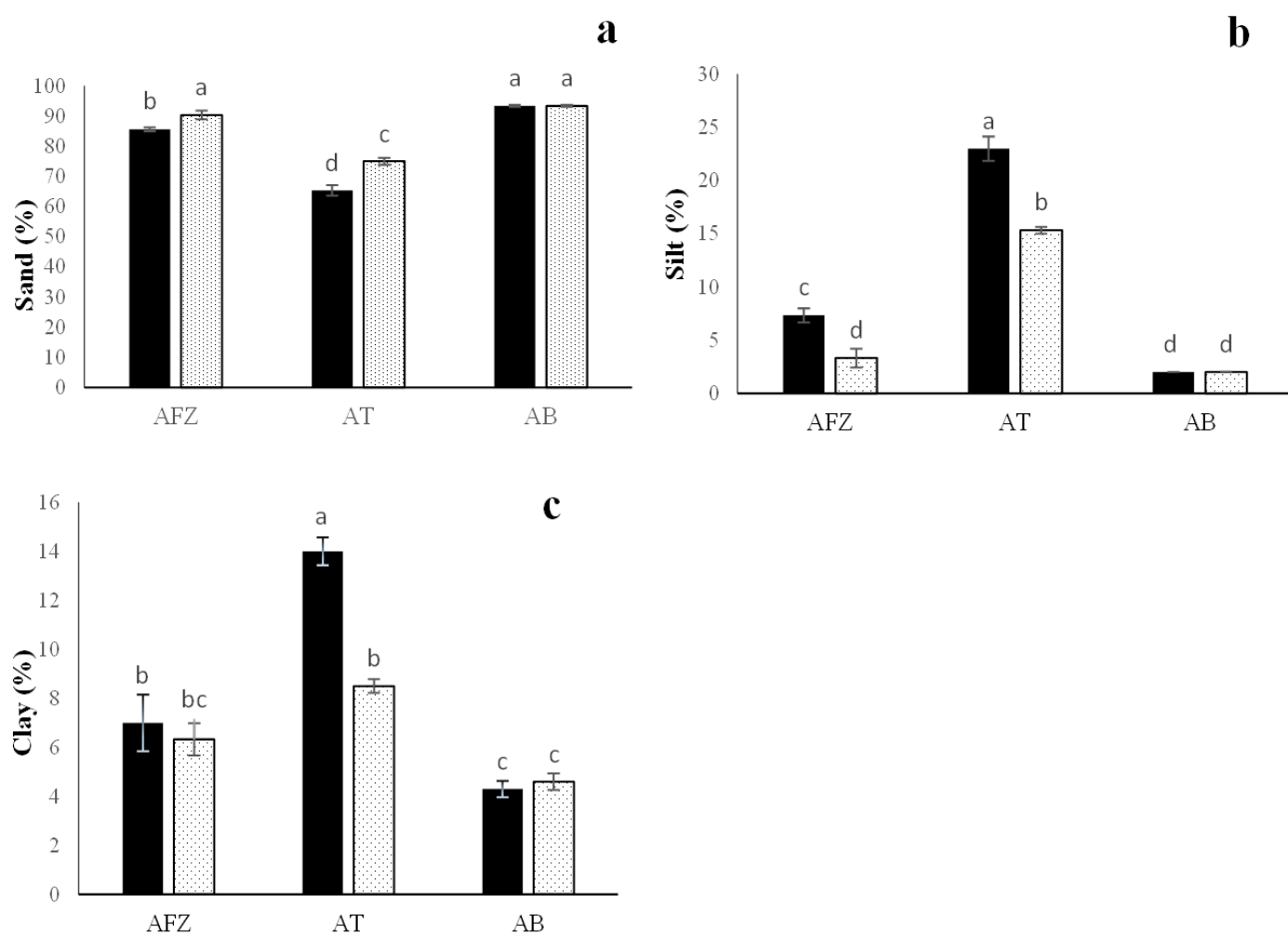


Figure 2

Sand (%) (a), silt (%) (b), and clay (%) (c) in *Ambrosia psilostachya* invaded (black), and uninvaded (control, white with dots) on the Anzali Free Zone (AFZ), Anzali town (AT) and Anzali beach (AB). Bars represent means ($n = 3$) $\pm$ SE. Bars topped by the same letter indicate no significant differences between treatments at the 5% level using Duncan's multiple-range test.

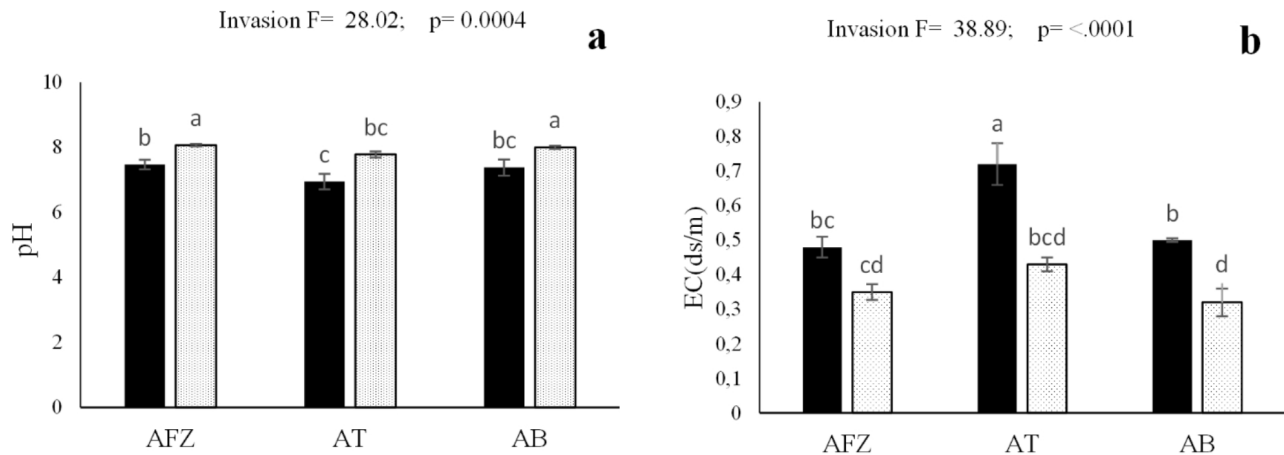


Figure 3

Soil pH (a), and EC (ds/m) (b) in *Ambrosia psilostachya* invaded, and uninvaded (control) on the Anzali Free Zone (AFZ), Anzali town (AT) and Anzali beach (AB). Bars represent means ($n = 3$) $\pm$ SE Bars topped by the same letter indicate no significant differences between treatments at the 5% level using Duncan's multiple-range test.

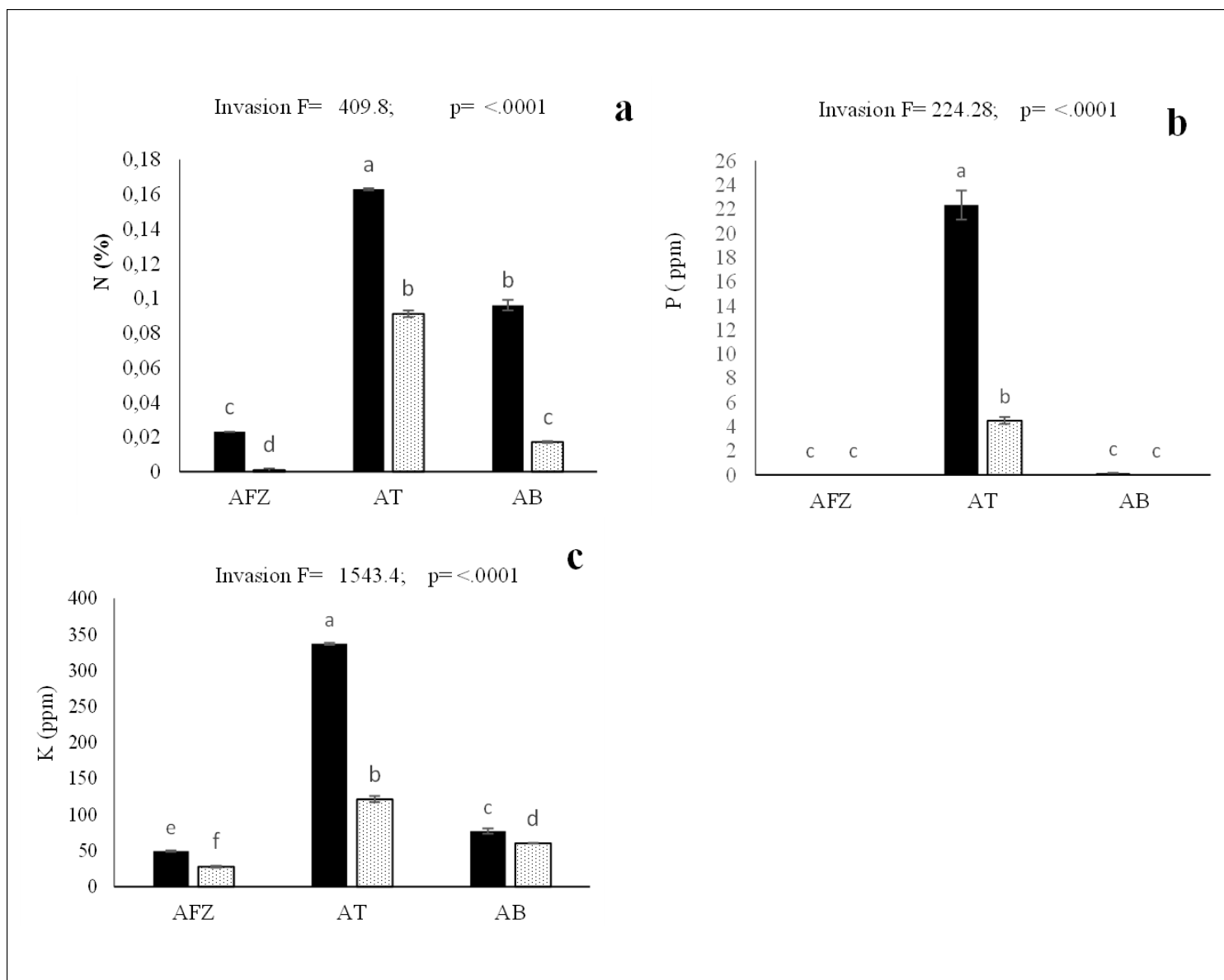


Figure 4

Concentrations of N (%) (a), P (ppm) (b), and K (ppm) (c) in *Ambrosia psilostachya* invaded and uninvaded (control) on the Anzali Free Zone (AFZ), Anzali town (AT) and Anzali beach (AB). Bars represent means (n = 3) $\pm$ SE. Bars topped by the same letter indicate no significant differences between treatments at the 5% level using Duncan's multiple-range test.

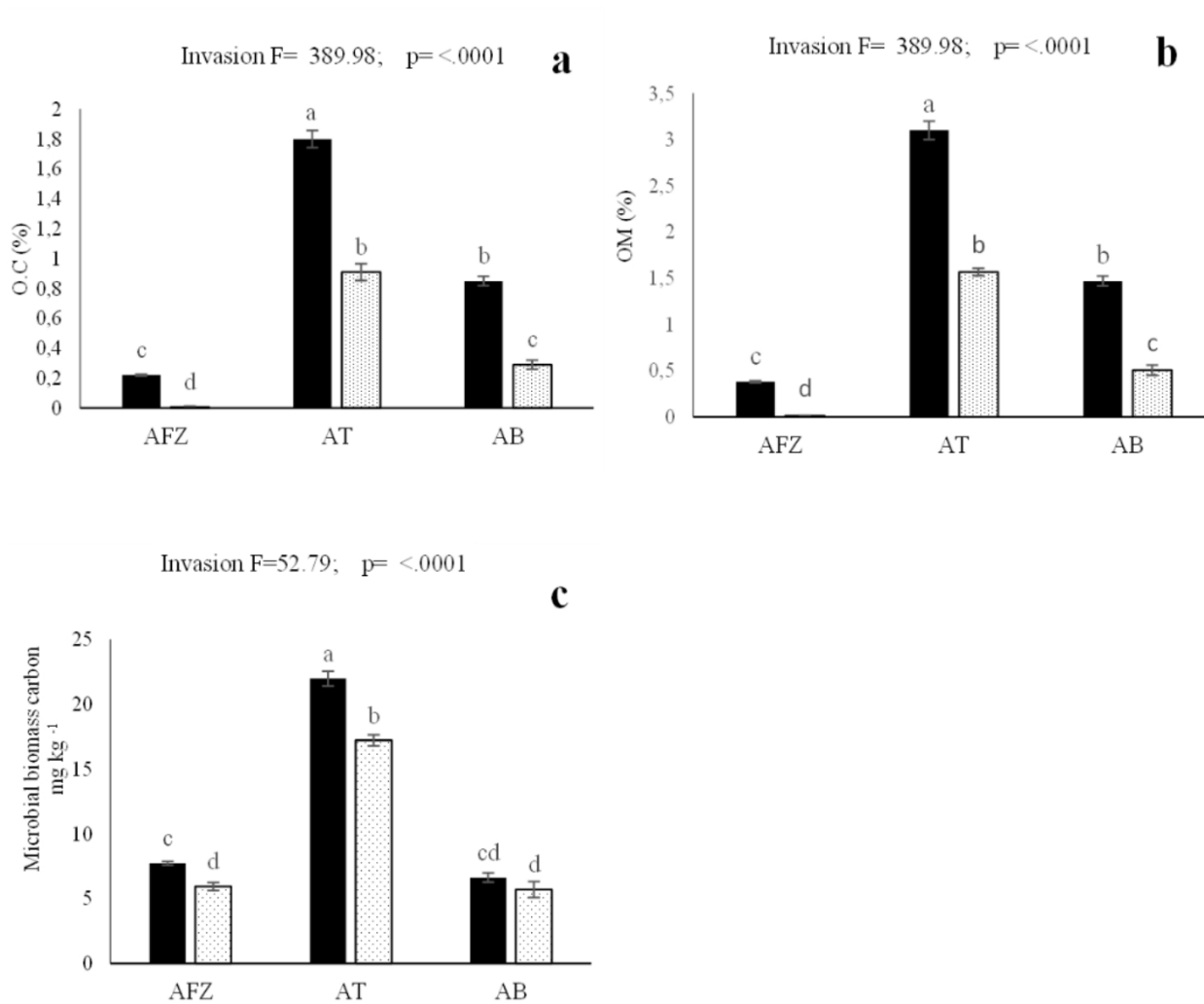


Figure 5

Soil organic carbon (O. C%) (a), Soil organic matter (O.M%), and microbial biomass carbon (mg kg⁻¹) (c) in *Ambrosia psilostachya* invaded, and uninvaded (control) on the Anzali Free Zone (AFZ), Anzali town (AT), and Anzali beach (AB). Bars represent means (n = 3) ± SE Bars topped by the same letter indicate no significant differences between treatments at the 5% level using Duncan's multiple-range.

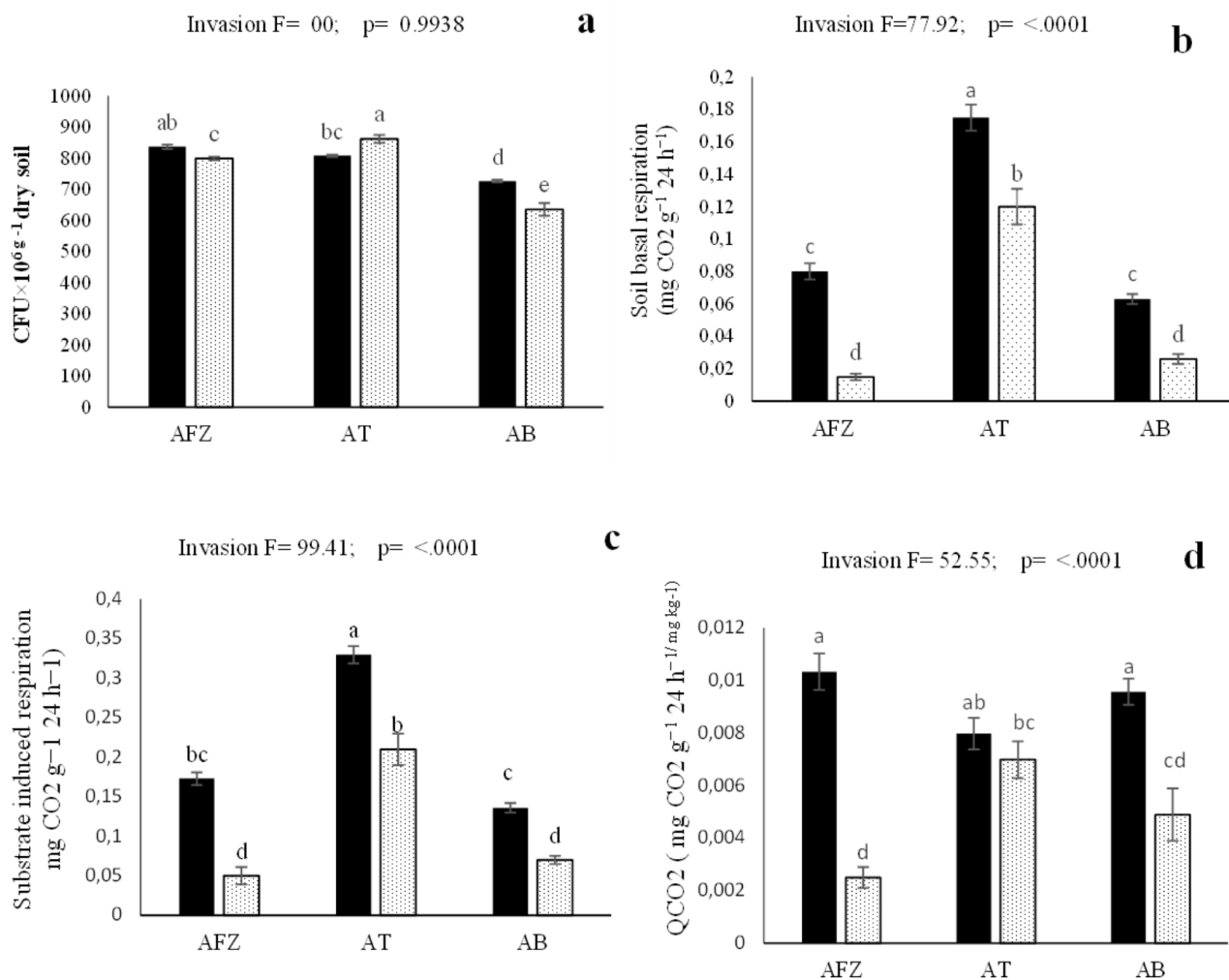


Figure 6

The numbers of total bacteria (CFU×10⁶ g⁻¹ dry soil) (a), microbial biomass carbon (mg kg⁻¹) (a), soil basal respiration (mg CO₂ g⁻¹ 24 h⁻¹) (c), and substrate induced respiration (mg CO₂ g⁻¹ 24 h⁻¹) (d) in *Ambrosia psilostachya* invaded, and uninvaded (control) on the Anzali Free Zone (AFZ), Anzali town (AT), and Anzali beach (AB). Bars represent means (n = 3) ± SE Bars topped by the same letter indicate no significant differences between treatments at the 5% level using Duncan's multiple-range.