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Converting invasive aster (*Ageratina adenophora* L.) into organic fertilizer source

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ABSTRACT: *Ageratina adenophora* originated from Central America and is now flooding in tropical and subtropical countries where tobacco is the primary cash crop. *A. adenophora* is a noxious invasive plant affecting agriculture, forestry, and livestock production. After converting *A. adenophora* into an organic fertilizer source, the contents of nitrogen (N), phosphorus (P), and potassium (K) in *A. adenophora* and soil samples (rhizosphere and non-rhizosphere soil) collected from 42 typical *A. adenophora* communities were determined. *In-situ* composting (using cellulolytic decomposing bacteria *Clostridium thermocellum* and detoxifying bacteria *Pseudomonas putida*) and field experiment were conducted to compare the fertilizing effects with commercial organic fertilizer. The results showed that firstly, the nutrient contents of N, P, and K varied greatly with growth conditions (N 4.59–15.09 g/kg, P 0.71–5.46 g/kg, and K 7.44–17.65 g/kg). Secondly, NPK nutrients were mainly allocated in the shoots, and the NPK concentrations were comparable to those in shoot parts of rice, maize, and wheat. Depending on growth environments and soil properties, the more fertile soils, the more NPK nutrient contents accumulated. Lastly, applying decomposed *A. adenophora* gained high-medium tobacco proportion of 89.1% relative to that applied with commercial organic fertilizer (88.6%) ($p > 0.05$). Applying the decomposed *A. adenophora* on the experimental field could generate a slightly higher income than using commercial organic fertilizer. Therefore, *A. adenophora* is supposed to be NPK-rich organic fertilizer source, and the fertilizing effects were comparable to commercial organic fertilizer for promoting flue-cured tobacco yield and quality.

KEYWORDS: *Ageratina adenophora*, N/P/K in plant and soil, organic fertilizer, rhizosphere soil

INTRODUCTION

Ageratina adenophora is a member of the daisy family, Compositae. Commonly known as crofton weed or sticky snakeroot, *A. adenophora* originated from Central America and now is widely spread in tropical and subtropical areas due to artificial introduction or natural transmission such as China, America, India, Brazil, Zimbabwe, etc., where tobacco is a primary cash crop with large planting areas. *A. adenophora* is a perennial noxious weed that has strong ecological adaptability. Specifically, *A. adenophora* not only overspreads rapidly in the environments with enough light, heat, water, and fertilizer supply, but is also tolerant to shade, low fertility stress, and drought [1, 2]. *A. adenophora* plant contains substances noxious to herbivores and surrounding plants. Horses eating *A. adenophora* plant leaves would suffer from asthma or even death [3]. Hepatotoxicity occurred in rats when fed with the extracts of *A. adenophora* plant leaves [4]. *A. adenophora* plants also release allelopathic substances into the surrounding soil through root secretion, plant residue rot, and rain leaching [5]. These allelopathic substances are toxic; the water-extracts of *A. adenophora* inhibits the seed germination and growth of other plants [6, 7]. This invasive species invaded China through the Sino-Burmese border in 1940s. It is almost 80 years after its first invading. Today, *A. adenophora* grows profusely in Yunnan, Guizhou, Sichuan, Chongqing, and Guangxi. *A. adenophora* is one of the most harmful invasive species in China [8]. In the 1970s, *A. adenophora* invaded Liangshan directly from Yunnan through Panzhihua [9]. In 2008, the impaired area in Liangshan reached 612 400 ha. Three years later, namely, in 2011, its coverage and biomass were up to 54 500 kg/ha, respectively [10, 11].

With *A. adenophora* spreading, the native plants grow worse and gradually die due to the adverse effects of allelopathic substances released from *A. adenophora* plants [12]. Even worse, the asexual and sexual reproducing ability accelerates *A. adenophora* spreading. Sooner or later, the local plant communities would be replaced by *A. adenophora* plants, which snatch soil nutrients, light, space, etc., with native plants, and finally *A. adenophora* plants would form a single dominant species community [13].

The combined application of control and utilization is proved to be a principal method in restraining the spreading of *A. adenophora* [13]. Despite tremendous ecological destruction, *A. adenophora* owns vast spreading area and great biomass. The resource utilization of *A. adenophora* plant residues obtained in artificial or mechanical controlling process of

A. adenophora can not only reduce the processing cost, but also achieve the goal of turning waste into treasure [13]. Attempts have been made to use the invasive plants as phytogenic pesticides [14], biofuels [15], chlorogenic acid sources [16], and biochar [17]. Nonetheless, none of these efforts have proven economically or practical. Consequently, *A. adenophora* plants have continuously spread in many tropical and subtropical countries [13]. It is urgently necessary to find a new, simple, and economical way to make use of the residue piles after the artificial and mechanical harvest of *A. adenophora* plants. The integration of control and utilization is an effective method to keep *A. adenophora* from spreading. Previous attempts showed *A. adenophora* contains more than 70 kinds of toxins and no forage value for animal husbandry unless the toxins are removed or decomposed [3]. Liang and Zhang [18] found that the fiber of *A. adenophora* was neither long enough for papermaking nor strong enough for building construction [19]. *A. adenophora* is not worth using as biofuel due to its low calorific value [20]. Additionally, it is impossible to incorporate the plants into soil because they grow on mountains or hills, and no rototillers are applicable in the region. Obviously, there is an urgent need to find a new way to use piled debris and litter after artificial control of *A. adenophora*. Applying organic manure and straw returning to the field are important practices to improve soil fertility and soil properties for crop production. The application of organic manure can balance nutrient (N, P, K, and trace elements) supply, maintain, or increase soil organic matter content, improve soil physical structure and microbial activities, and hence enhance nutrient bioavailability [21]. *A. adenophora* is a potential source of organic fertilizer because of its large biomass [22].

Studying the *A. adenophora* plants and their soil can benefit crop production by converting the invasive species into an organic fertilizer source. Liangshan Prefecture is severely invaded with more than 20% of the area covered by *A. adenophora* [23]. The prefecture is the main production base of flue-cured tobacco, vegetables, fruits, and other cash crops in Sichuan, which needs a great amount of organic fertilizer [24]. Lian [25] studied the feasibility of using decomposed *A. adenophora* as an onion-specific fertilizer. The results suggested that the decomposing effect of *A. adenophora* with a ripening agent was better than that of natural decomposing. Jiao et al [26] found that chemical fertilizer combined with organic fertilizer composed of *A. adenophora* significantly increased pepper yield. Consequently, in Liangshan, the *A. adenophora* shoots can be harvested as a quality organic fertilizer source.

The objectives of this study were to: (1) convert *A. adenophora* into an organic fertilizer source, and (2) evaluate the fertilizing effect of decomposed *A. adenophora* for tobacco production.

MATERIALS AND METHODS

Study sites and sample collection

There is one city and 16 counties in Liangshan Prefecture (100°15′–103°53′ E, 26°03′–29°27′ N) in Sichuan Province, China. The prefecture is adjacent to Guizhou and Yunnan. Indian Ocean monsoon climate dominates with annual means of temperature of 14–17 °C, daylight hours of 2000–2400 h, rainfall of 1000–1100 mm, and a frost-free period of 230–306 d. Liangshan consists of various topographies, geomorphologies, and complicated climate types ranging from south subtropical to north temperate climates [27].

Based on the distribution of *A. adenophora*, 42 typical sites accounting for more than 95 coverage were selected as sampling sites in 7 counties (cities) in Liangshan Prefecture of Sichuan Province, China in August 2018. *A. adenophora* plant tissues, rhizosphere, and non-rhizosphere soil samples were collected (Table S1). The 42 pairs of soil samples were collected by the root-shaking method [28]. The bulk soil on the root was shaken off as non-rhizosphere soil. The soil that adhered to the root surface was removed with a brush as rhizosphere soil. This process was repeated with 3 plant roots.

Soil and plant sample analysis

Fresh plant samples were treated with high temperature desiccation at 105 °C for 15min, then placed in the oven at 65 ± 1 °C for 24 h, and dried to constant weight, and then the leaves, roots, and stems were digested with H_2SO_4-H_2O_2 [29]. After that, the total N levels were measured by semi-micro Kjeldahl method with Kjeltec Auto 1030 analyzer (Tecator, Sweden), total P levels were determined via molybdenum antimony colorimetric method on a type 721 spectrophotometer (Shanghai Precision & Scientific Instrument Co., Ltd., Shanghai, China), and total K levels were detected using a flame spectrophotometer (AP1200 type, Shanghai Aopu Analytical Instrument Co., China) [30]; the determination of humic acid was performed according to the national standards of the People's Republic of China (GB/T 11957-2001). The soil samples were air-dried after picking out the rock/gravel and plant debris. Then, soil organic carbon (SOC) was measured with the K_2CrO_7-Fe_2SO_4 method; total nitrogen (TN) was measured by the Kjeldahl method, total phosphorus (TP) was determined by NaOH fusion and dry ashing method, and total potassium (TK) was detected by NaOH fusion and flame-photometric method. To measure alkali-hydrolysable nitrogen, the soil and $FeSO_4 \cdot 7H_2O$-Ag_2SO_4 were mixed evenly at weight ratio of 2:1, and then added to 1 N NaOH solution. After incubated at 40 °C for 24 h, HCl titration was used to measure NH_3 absorbed in 2% H_3BO_3 solution [31]. Olsen extractable phosphorus was extracted by 0.5 M $NaHCO_3$ and measured with colorimetric molybdenum-blue method. Available potassium was extracted by 1 M NH_4OAc (pH 7) and detected with a flame photometer (Shanghai Yidian Analysis Instrument Co., Ltd., China) [30].

In-situ composting of *A. adenophora* plants

The shoots (stem and leaf) of *A. adenophora* plants were mechanically cut into 2–3 cm segments for the sake of proper decomposition. At 2‰ inoculum (10^{10} CFU/g mixed *Clostridium thermocellum* and *Pseudomonas putida* obtained from Chongqing Organic Biotech Co., Ltd., China), *C. thermocellum* grew the fastest at 32.5 °C and stopped reproducing at 63.5 °C; *P. putida* could use benzene, phenanthrene, and pyrene as energy sources, and it grew the fastest at 29.0 °C and stopped reproducing at 51.0 °C. In the composting process of *A. adenophora*, the high temperature period (50.0–64.5 °C) would last for 21 d [32]. 1.5‰ urea and 1‰ lime (weight ratio) was evenly mixed into the segments. Adding urea was to enhance the N level, thus improving the activity of microorganisms, and lime was for adjusting pH > 7, which was beneficial for the decomposition. About 2000 kg mixed segments were piled and covered with a plastic film to preserve heat and moisture. After 45–60 d, *A. adenophora* segments were fully decomposed and ready for use. The decomposed *A. adenophora* (pH 7.56) contained 90.34% organic matter, 2.73% N, 0.75% P_2O_5, 2.66% K_2O, and 8.39% humic acid. The commercial organic fertilizer (pH 7.47) contained 45% organic matter, 2.8% N, 1.42% P_2O_5, and 0.97% K_2O with no humic acid detected.

Field fertilizer effect experiment

Test material

Flue-cured tobacco is the primary industry for Mianning County in Liangshan. The local prevailing cultivar, 'Yun 95', was employed in this study. The tobacco seedlings were provided by Mianning Tobacco Company.

General situation of the experimental site

The field experiment was conducted in Mianning County (28°30′37″ N, 102°07′55″ E) of Sichuan Province, China. The brown soil, which is widespread in the local area, had medium loam texture (Eutric Regosol, UAO Soil Taxonomic System) with pH 5.12 and contained 22.36 g/kg organic matter, 1.82 g/kg total nitrogen, 0.73 g/kg total phosphorus, 20.61 g/kg total potassium, 180.65 mg/kg alkali-hydrolysable nitrogen, 65.35 mg/kg Olsen phosphorus, and 202.18 mg/kg available potassium.

Experimental design

The field experiment was conducted from April to October 2018. Considering the real tobacco fertilizer management in the local areas, the treatments were a blank control (CK) and 2 fertilizer treatments including: (1) 50% commercial organic fertilizer + 50% chemical fertilizer (CCF); and (2) 50% decomposed *A. adenophora* + 50% chemical fertilizer (ACF) (Fig. 1). The plot area was 132 m^2 (6.6 m × 20 m). The randomized complete block design was used with 3 replications. CCF was fertilized pre-plant with commercial organic fertilizer (2.8:1.42:0.97) at 1650 kg/ha and ACF with decomposed *A. adenophora* at 1650 kg/ha. Both treatments were also applied with 225 kg/ha potassium nitrate and 200 kg/ha tobacco specific compound fertilizer (10:10:25) on 10 d and 40 d after transplanting. Meanwhile, single-nutrient chemical fertilizers were applied to keep N, P_2O_5, and K_2O at the same level for both CCF and ACF; the applied amount of N, P_2O_5, and K_2O were 91.5, 73.5, and 267.5 kg/ha, respectively. Field management practices, harvest, and flue-curing of tobacco were all implemented in accordance with local high-quality tobacco production technical specifications.

Sample collection

The respective soil samples of ACF and CCF were collected before transplanting and after harvesting by the five-point sampling method [33]. Flue-cured tobacco leaf grading was completed according to 42-level national grading standard (GB2635-1992), and flue-cured tobacco leaves at grades of B2F, C3F, and X2F (representing upper, middle, and lower leaves) were sampled separately for chemical analysis.

Yield and quality indicator analysis

Tobacco leaves were harvested by plot at maturity stage and then baked by adopting three-stage curing process [34]. Thereby, the flue-cured tobacco yield, income, and the proportion of middle- and high-grade flue-cured tobacco were recorded for each plot. The chemical properties of flue-cured tobacco, including the contents of nicotine, total sugar, reducing sugar, total nitrogen, K, and Cl, were analyzed by using MPA (model population analysis) near infrared spectrometer (Bruker Optik GmbH, Ettlingen, Germany) [35]. The reducing sugar-total sugar ratio and K-Cl ratio were calculated. As it could be predicted that CK treatment always has the lowest yield, income, and soil available nutrients, we did not give out the data of CK here to clearly compare the performances of CCF and ACF.

Data processing

All data were subjected to one-way ANOVA analysis by using the software SAS 9.4 (SAS Institute Inc., Cary, NC, USA), including the contents of N, P, and K in root, stem, and leaf of *A. adenophora* plants, the chemical indicators of flue-cured tobacco between CCF and ACF treatments, the soil physicochemical traits of basal soil,

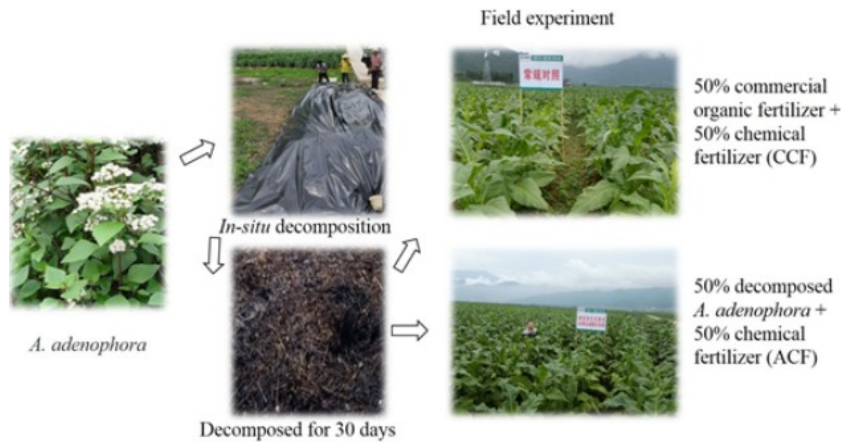

Fig. 1 *In-situ* decomposed *A. adenophora* is an environment-friendly organic fertilizer.

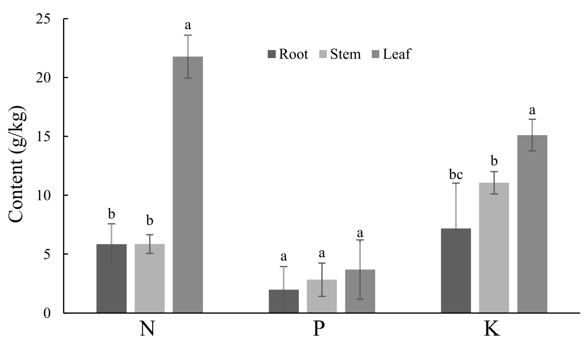

Fig. 2 Contents of N, P, and K in the root, stem, and leaf of *A. adenophora*. N, P, and K represent nitrogen, phosphorus, and potassium in *A. adenophora* plant; different letters of the same nutrient are significantly different at $p < 0.05$ level.

CCF, and ACF treatments. The correlations of N, P, and K contents in *A. adenophora* plants with organic matter (OM), total nitrogen (TN), total phosphorus (TP), total potassium (TK), alkaline nitrogen (AN), available phosphorus (AP), and available potassium (AK) in the non-rhizosphere soil were analyzed. The least significant difference (LSD) was employed for multiple comparisons between treatment means. The mean difference is considered significant when $p < 0.05$.

RESULTS

Nitrogen, phosphorus, and potassium contents in plants

The contents of N, P, and K in *A. adenophora* plants were 9.28 (4.59–15.09), 2.88 (0.71–5.46), 11.67 (7.44–17.65) g/kg on average, respectively (Table S2). The great variations were attributed to the even greater variations of soil nutrients, and this also indicated that *A. adenophora* plants had strong nutrient-absorbing ability and could adapt to soils with different fertility.

A. adenophora leaves had the greatest N content of 21.77 g/kg on average; those of the stems and roots were 5.84–5.86 g/kg. P content was 3.69, 2.83, and 1.98 g/kg for the leaves, stems, and roots on average, respectively. The K content was leaf (15.11 g/kg) > stem (11.06 g/kg) > root (7.19 g/kg) (Fig. 2).

Total soil nutrients

The TN and TP contents were greater in rhizosphere (1.49 and 0.71 g/kg, respectively) than in non-rhizosphere (1.00 and 0.65 g/kg, respectively). Nevertheless, corresponding TK contents were similar in rhizosphere and non-rhizosphere (19.89 and 20.31 g/kg, respectively) (Table S2).

Soil organic carbon and available nutrients

Soil organic carbon (SOC) was significantly greater in rhizosphere (24.38 g/kg) than in non-rhizosphere (15.02 g/kg). Alkali-hydrolysable nitrogen was greater in rhizosphere (70.83 mg/kg) than in non-rhizosphere (51.92 mg/kg), and Olsen phosphorus was similar in both rhizosphere (22.95 mg/kg) and non-rhizosphere (21.37 mg/kg). Available potassium was significantly greater in rhizosphere (163.94 mg/kg) than in non-rhizosphere (110.95 mg/kg). The CV values were significantly lower in rhizosphere than in non-rhizosphere (Table S3).

Correlations between plant and soil nutrients

As shown in Table S4, N content in *A. adenophora* was closely correlated with TN and AN in non-rhizosphere soil. P content in *A. adenophora* was closely associated with TP and AP in non-rhizosphere soil. K content in *A. adenophora* was significantly correlated with AK in non-rhizosphere soil. The correlations suggested that the soil nutrients had a strong influence on N, P, and K contents in *A. adenophora*.

P content in *A. adenophora* was significantly correlated with TP and AP, and K content in *A. adenophora*

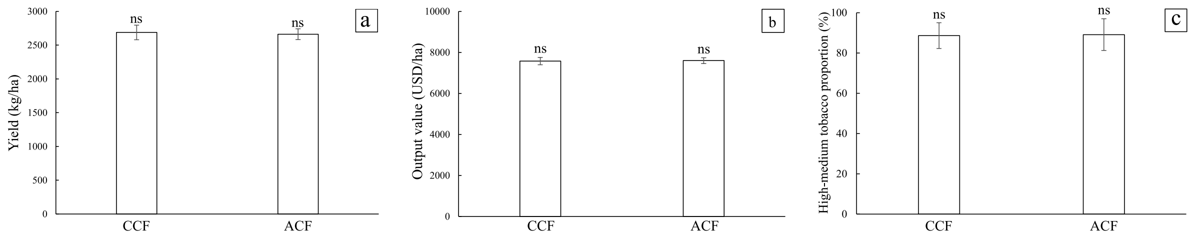

Fig. 3 Economic traits of flue-cured tobacco of CCF and ACF. Bars represent standard deviations. CCF and ACF represent treatments applied with conventional commercial organic fertilizer and decomposed *A. adenophora*, respectively; Different letters in the same figure indicate significant difference at $p < 0.05$ level.

had a significant correlation with AK in rhizosphere soil.

Economic traits of flue-cured tobacco

As shown in Fig. 3, CCF had the greatest yield (2687.5 kg/ha), and ACF was of the greatest income ($7600/ha). There was not any significant difference in proportion of high and medium tobacco (89.1%) between CCF and ACF.

Chemical characteristics of flue-cured tobacco

Total nitrogen was greater in ACF than in CCF; the contents in B2F, C3F, and X2F tobacco leaves were greater in ACF than in CCF by 41.35%, 5.16% and 7.59%, respectively. Nicotine contents in B2F, C3F, and X2F tobacco leaves of ACF were, in varying degrees, greater than CCF by 66.93%, 17.48% and 34.29%, respectively. Total sugar and reducing sugar had no significant change regulation; the ratio of reducing sugar to total sugar ranged in 67.85%–80.87%. Contents of K and Cl in different parts of ACF were lower than those of CCF in varying degrees, and the K-Cl ratio increased by 14.83%–102.38% (Table 1).

Physicochemical properties of tobacco-planting soil

As shown in Table 2, the OM was significantly lower in ACF than in both basal soil and CCF. AN and AP were in this order: CCF > basal soil > ACF. There was significant difference in each two of them. Nevertheless, AK was ACF > basal soil > CCF; the difference in each two of them was significant.

DISCUSSION

According to a field investigation, *A. adenophora* invades various land types such as grassland, sparse woodland, and disturbed lands. The altitude ranged from 900 m to 2200 m. *A. adenophora* can survive not only in fertile soil, but also in barren soil [36].

Plant nutrient contents can reflect the nutrient uptake ability in certain habitat conditions and reveal the growth and development status to some extent. N, P, and K are the most important nutrients essential for plant growth and development. Without human intervention, wild plants acquire nutrients mainly from the growth environment. Among the 42 typical communities, the respective maximum N, P, and K contents were 3.29, 7.69, and 2.37 times that of the corresponding minimum values. The positive correlations between N content in *A. adenophora* and soil N level indicated that soil N level significantly influenced *A. adenophora*'s absorption rates of N. The relationship of each of the other nutrients such as P and K between the two is similar as N. The more fertile the soil is, the more N, P, and K in *A. adenophora* are absorbed. The N content in *A. adenophora* had no correlation with TN and AN in the rhizosphere soil; this noncorrelation was attributed to that the N absorption by the *A. adenophora* root was faster than soil nitrogen diffusion. Furthermore, a relative deficit zone possibly existed in the rhizosphere soil. On the contrary, the correlations of P concentration in *A. adenophora* with P in both rhizosphere and non-rhizosphere soils suggested that the *A. adenophora* root can activate and utilize sparsely soluble phosphates. The positive relationship between K content in *A. adenophora* and AK in soil indicated that K content in *A. adenophora* was mainly determined by the soil AK level. Therefore, *A. adenophora* had a strong acquisition ability of N, P, and K. The strong N acquisition caused an N depletion circle in the rhizosphere soil; at the same time, the soil P and K were activated obviously. Previous studies have shown that *A. adenophora* can secrete through the root large amounts of geranic acid, benzoic acid, and dibutyl phthalate, etc [37, 38]. Hence, the increments of AP and AK in the rhizosphere soil are possibly correlated with organic acids in root exudate, which need to be verified in further study.

Plant nitrogen, phosphorus, and potassium contents and allocations may reveal the nutrient acquisition ability of *A. adenophora* in various habitats to some extent. N content in *A. adenophora* followed this order: leaf > stem ≈ root. Both of P and K contents obeyed this sequence: leaf > stem > root. Consequently, N, P, and K mainly accumulated in the shoots; this nutrient accumulation may be attributed to that leaves and stems played the roles of photosynthesis and nutrient assimilation, thus large amount of nutrients were needed.

Table 1 Chemical indicators of flue-cured tobacco of CCF and ACF treatments.

Treatment	Part	Nicotine (%)	Total sugar (%)	Reducing sugar (%)	Total N (%)	K (%)	Cl (%)	Reducing sugar-total sugar ratio (%)	K-Cl ratio
CCF	B2F	1.27^{bc}	31.04^{b}	22.82^{c}	2.08^{b}	1.72^{b}	0.23^{b}	73.52^{ab}	7.48^{b}
	C3F	1.43^{b}	34.55^{a}	24.18^{ab}	2.13^{b}	2.08^{a}	0.45^{a}	69.99^{ab}	4.62^{c}
	X2F	1.05^{c}	33.39^{ab}	25.77^{a}	2.37^{b}	1.87^{ab}	0.42^{a}	77.18^{a}	4.45^{c}
ACF	B2F	2.12^{a}	25.41^{d}	19.74^{d}	2.94^{a}	1.99^{a}	0.19^{b}	77.69^{a}	10.47^{a}
	C3F	1.68^{ab}	35.24^{a}	23.91^{b}	2.24^{b}	2.15^{a}	0.23^{b}	67.85^{b}	9.35^{a}
	X2F	1.41^{b}	29.33^{c}	23.72^{b}	2.55^{ab}	1.94^{a}	0.38^{a}	80.87^{a}	5.11^{c}

CCF and ACF represent treatments applied with conventional commercial organic fertilizer and decomposed *A. adenophora*, respectively; B2F, C3F, and X2F are the grades of flue-cured tobacco leaves located at upper, central, and bottom parts of tobacco plant, respectively; different letters in the same column indicate significance of difference at $p < 0.05$ level.

Table 2 Soil physiochemical traits of basal soil, CCF, and ACF treatments.

Sampling time	Treatment	pH	OM (g/kg)	TN (g/kg)	TP (g/kg)	TK (g/kg)	AN (mg/kg)	AP (mg/kg)	AK (mg/kg)
Before planting	Basal soil	5.68^{a}	65.58^{a}	1.79^{a}	2.04^{a}	7.57^{b}	131.53^{b}	41.87^{b}	241.18^{b}
After harvesting	CCF	5.27^{a}	63.13^{a}	0.63^{b}	2.35^{a}	10.17^{a}	183.54^{a}	59.41^{a}	186.18^{c}
	ACF	5.60^{a}	39.69^{b}	1.74^{a}	2.31^{a}	12.57^{a}	74.33^{c}	38.69^{c}	313.21^{a}

CCF and ACF represent treatments applied with conventional commercial organic fertilizer and decomposed *A. adenophora*, respectively; OM, TN, TP, TK, AN, AP, and AK represent organic matter, total nitrogen, total phosphorus, total potassium, alkali-hydrolysable nitrogen, available phosphorus, and available potassium in *A. adenophora* growing soil; different letters in the same column indicate significance of difference at $p < 0.05$ level.

Crop biomass or residue is one of the main sources of organic fertilizer. The respective level of N, P, and K is 9.1, 1.3, and 18.9 g/kg in rice straw, 9.2, 1.52, and 11.8 g/kg in corn stalks, and 6.5, 0.8, and 11.8 g/kg in wheat straw [39, 40]. Compared with the aforementioned crops, *A. adenophora* is abundant in N, P, and K (9.37, 2.88, and 11.67 g/kg, respectively), especially P content; it was 3.6 times that of wheat straw.

Compared with commercially used organic fertilizer, decomposed *A. adenophora* had a few advantages over conventional commercial organic fertilizer: (1) Flue-cured tobacco of ACF and CCF produced respectively 89.1% and 88.6% of medium- and high-quality tobacco by aroma and taste; (2) ACF and CCF generated incomes of US$7600/ha (53 128.5 Yuan/ha) and US$7574/ha (52 947.7 Yuan/ha); (3) ACF improved the chemical properties of flue-cured tobacco with more coordinating; (4) ACF significantly increased the contents of nicotine and total nitrogen; (5) ACF decreased total sugar and reducing sugar contents in some extent; and (6) ACF improved the K-Cl ratio to an extent. Additionally, decomposed *A. adenophora* may prevent soil from acidification and enhance soil nutrient supply.

CONCLUSION

As a noxious weed, *A. adenophora* has spread in a variety of habitats throughout southwest China. This study with 42 typical invaded communities in the area showed that the species is rich in nutrients such as N, P, and K in the shoot systems. The nutrient levels varied greatly with its growth environment. Decomposing the shoots with mixed bacteria *C. thermocellum* and *P. putida* converted this invasive species *in-situ* into a promising organic fertilizer source, whose fertilizing effects were like tobacco specific compound fertilizer commercially available for flue-cured tobacco production. The low-cost *in-situ* produced organic fertilizer may motivate local farmers to maximize the economic and ecological benefits and minimize invading the noxious weed by smart use of the weed.

Appendix A: Supplementary data

Supplementary data associated with this article can be found at http://dx.doi.org/10.2306/scienceasia1513-1874.2022.038.

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REFERENCES

1. Sheng Q (1998) The history and status of the study on Crofton weed (*Eupatorium adenophorum* Spreng.) a worst worldwide weed. *J Wuhan Bot Res* **4**, 366–372. [in Chinese]
2. Lu P, Sang WG, Ma KP (2006) Effects of environmental factors on germination and emergence of crofton weed (*Eupatorium adenophorum*). *Weed Sci* **54**, 452–457.
3. O'Sullivan B (1979) Crofton weed (*Eupatorium adenophorum*) toxicity in horses. *Aust Vet J* **55**, 19–21.

4. Kaushal V, Dawra RK, Sharma OP, Kurade NP (2001) Hepatotoxicity in rat induced by partially purified toxins from *Eupatorium adenophorum* (*Ageratina adenophora*). *Toxicon* **39**, 615–619.
5. Xu RG, Weng JH, Hu LW, Peng GN, Ren ZH, Deng JL, Jia Y, Wang CM, et al (2018) Anti-NDV activity of 9-oxo10,11-dehydroageraphorone extracted from *Eupatorium adenophorum* Spreng *in vitro*. *Nat Prod Res* **32**, 2244–2247.
6. Wang SQ, He SL, Zhang MZ, Zhang YX, Wang QY, Zhang CY, Liu TY, Liu B, et al (2020) Chemical composition and allelopathic potential of essential oils from *Eupatorium maculatum* on *Lolium perenne* L. and *Echinochloa crus-galli* L. *Allelopathy J* **49**, 51–62.
7. Ma JH, Feng XX, Yang XH, Cao YH, Zhao WF, Sun LL (2020) The leaf extract of crofton weed (*Eupatorium adenophorum*) inhibits primary root growth by inducing cell death in maize root border cells. *Plant Divers* **42**, 174–180.
8. Sang W, Zhu L, Axmacher JC (2010) Invasion pattern of *Eupatorium adenophorum* Spreng in southern China. *Biol Invasions* **12**, 1721–1730.
9. Gui FR, Wan FH, Guo JY (2008) Population genetics of *Ageratina adenophora* using inter-simple sequence repeat (ISSR) molecular markers in China. *Plant Biosyst* **142**, 255–263.
10. Zhang XY, Tang CJ, Zhou S, Hou Z, Zhang XX, He P, Hu X (2008) *Eupatorium adenophorum* monitoring report of Sichuan in 2006. *Pratac Sci* **7**, 91–98. [in Chinese]
11. Zhang JH (2015) *Prevention and Control of Eupatorium adenophorum*, Chemical Industry Press, Beijing, China.
12. Thapa LB, Kaewchumnong K, Sinkkonen A, Sridith K (2020) "Soaked in rainwater" effect of *Ageratina adenophora* on seedling growth and development of native tree species in Nepal. *Flora* **263**, ID 151554.
13. Poudel AS, Jha PK, Shrestha BB, Muniappan R (2019) Biology and management of the invasive weed *Ageratina adenophora* (Asteraceae): current state of knowledge and future research needs. *Weed Sci* **59**, 79–92.
14. Wang YD (2002) The studies on the extraction, isolation, purification, identification and aphid-killing mechanism of the active aphid-killing substances from *Eupatorium adenophorum*. PhD thesis, Sichuan Univ, China.
15. Zhang B, Zhong Z, Chen P, Ruan R (2017) Microwave-assisted catalytic fast co-pyrolysis of *Ageratina adenophora* and kerogen with CaO and ZSM-5. *J Anal Appl Pyrolysis* **127**, 246–257.
16. Zhang M, Liu WX, Zheng MF, Xu QL, Wan FH, Wang J, Lei T, Zhou ZY, et al (2013) Bioactive quinic acid derivatives from *Ageratina adenophora*. *Molecules* **18**, 14096–14104.
17. Fan L, Zhou X, Liu Q, Wan Y, Cai J, Chen W, Chen FH, Ji L, et al (2019) Properties of *Eupatorium adenophora* Spreng (crofton weed) biochar produced at different pyrolysis temperatures. *Environ Eng Sci* **36**, 937–946.
18. Liang XY, Zhang XQ (2004) Occurrence characteristics, control, and utilization of *Eupatorium adenophorum*. *J Sichuan Grassl* **2**, 13–15. [in Chinese]
19. Sun JK, Chen KC, Jiao T, Luo Q, Guo J (2016) Experiment study of physicomechanical behavior of Xigeda soil reinforced by *Eupatorium adenophorum*. *Ind Constr* **46**, 124–127.
20. Jiang YH, Yu XH (1986) The study of producing marsh gas from *Eupatorium adenophorum* Spreng. *Acta Energ Sol Sin* **3**, 288–294. [in Chinese]
21. Wang X, Jia Z, Liang L, Zhao Y, Yang B, Ding R, Wang J, Nie J (2018) Changes in soil characteristics and maize yield under straw returning system in dryland farming. *Field Crop Res* **218**, 11–17.
22. Li P, Chang Q, Wang C, Cao J, Zheng W (2014) Composting of aerial parts of crofton weed (*Eupatorium adenophorum* Spreng), the top invasive plant in southwest China. *Compost Sci Util* **22**, 132–137.
23. Liu H, Du RW, Wang Y, Chen YL, Wu YK, Yuan L (2017) Effects of *Eupatorium adenophoruman* on interspecific association and the stability of companion species in Liangshan Prefecture of Sichuan Province. *Shengtai Xuebao* **37**, 5031–5038.
24. Wang B, Li M, Wen X, Yang Y, Zhu J, Belzile N, Chen YW, Liu M, et al (2020) Distribution characteristics, potential contribution, and management strategy of crop straw and livestock-poultry manure in multi-ethnic regions of China: A critical evaluation. *J Clean Prod* **274**, ID 123174.
25. Lian Z (2014) Discussion on the feasibility of taking *Eupatonium adenophornium* as onion basal fertilizer. *Hunan Agri Machy* **41**, 129–130. [in Chinese]
26. Jiao YJ, Sang YJ, Yang L, Wang YQ, Wu YK, Du RW, Yuan L (2016) Effects of fresh and composted *Ageratina adenophora* on physiology of three solanaceae vegetables and yield and quality of pepper. *Sci Agric Sin* **49**, 874–884.
27. Wang B, Qu J, Feng S, Chen T, Yuan M, Huang Y, Liao J, Yang R, et al (2019) Seasonal variations in the chemical composition of Liangshan olive leaves and their antioxidant and anticancer activities. *Foods* **8**, ID 657.
28. Riley D, Barber S (1969) Bicarbonate accumulation and pH changes at the soybean (*Glycine max* (L.) Merr.) root-soil interface 1. *Soil Sci Soc Am J* **33**, 905–908.
29. Thomas RL, Sheard RW, Moyer JR (1967) Comparison of conventional and automated procedures for nitrogen, phosphorus, and potassium analysis of plant material using a single digestion. *Agron J* **59**, 240–243.
30. Sparks DL, Page AL, Helmke PA, Loeppert RH, Swift RS (1996) *Methods of Soil Analysis, Part 3: Chemical Methods (Vol 14)*, John Wiley & Sons Inc., New York, NY.
31. Pansu M, Gautheyrou J (2006) *Handbook of Soil Analysis. Mineralogical, Organic and Inorganic Methods*, Springer-Verlag, Heidelberg, Germany.
32. Yang HJ, Du RW, Wu YK, Wang J, Wang Y, Zhao J, Liang YJ, Zhang CH, et al (2017) Microbial composting and detoxification of *Ageratina adenophora*. *Acta Pratac Sin* **26**, 131–138. [in Chinese]
33. Gregorich EG, Carter MR (2007) *Soil Sampling and Methods of Analysis*, CRC Press, Florida, USA.
34. Wang Y, Qin L (2021) Research on state prediction method of tobacco curing process based on model fusion. *J Ambient Intell Humaniz Comput* **15**, 1–11.
35. Jiang W, Han G, Zhang Y, Wang M (2010) Fast compositional analysis of ramie using near-infrared spectroscopy. *Carbohydr Polym* **81**, 937–941.
36. Gu C, Tu Y, Liu L, Wei B, Zhang Y, Yu H, Wang X, Yangjin Z, et al (2021) Predicting the potential global distribution of *Ageratina adenophora* under current and future climate change scenarios. *Ecol Evol* **11**, 12092–12113.
37. Thapa LB, Kaewchumnong K, Sinkkonen A, Sridith K (2017) Plant invasiveness and target plant density: high

densities of native *Schima wallichii* seedlings reduce negative effects of invasive *Ageratina adenophora*. *Weed Res* **57**, 72–80.

38. Jin YN (2010) Isolation and identification from root exudates of *Ageratina adenophora* (Asteraceae) and evaluation of their impact. PhD thesis, Southwest Univ, China.
39. Gao LW, Ma L, Zhang WF, Wang FH, Ma WQ, Zhang FS (2009) Estimation of nutrient resource quantity of crop straw and its utilization situation in China. *Trans Chin Soc Agric Eng* **25**, 173–179. [in Chinese]
40. Yao SM, Chen CL (2011) *New-type Fertilizer Application Guidance*, Chemical Industry Press, Beijing, China.

Appendix A. Supplementary data

Table S1 Basic information of sampling sites in the 7 counties (cities) in Liangshan Prefecture of Sichuan Province, China.

Site no.	Location	Altitude (m)	Remark
1	Huidong County (26°31′54″ N, 102°30′34″ E)	2030	Roadside
2	Huidong County (26°34′41″ N, 102°22′10″ E)	1840	Farmland
3	Huili County (26°31′39″ N, 102°8′22″ E)	1675	Ditch side
4	Huili County (26°31′13″ N, 102°8′35″ E)	1730	Roadside
5	Huili County (26°41′55″ N, 102°13′40″ E)	1900	Ditch side
6	Huili County (26°35′8″ N, 102°13′32″ E)	1863	Forest land
7	Huili County (26°35′8″ N, 102°13′34″ E)	1853	Roadside
8	Huili County (26°48′25″ N, 102°16′18″ E)	2150	Roadside
9	Dechang County (27°23′23″ N, 102°13′7″ E)	1310	Roadside
10	Dechang County (27°30′39″ N, 102°11′46″ E)	1430	Roadside
11	Puge County (27°37′8″ N, 102°26′23″ E)	1870	Farmland
12	Puge County(27°45′28″ N, 102°19′55″ E)	1900	Forest land
13	Ningnan County (27°3′42″ N, 102°46′5″ E)	1300	Roadside
14	Ningnan County (27°4′50″ N, 102°43′57″ E)	1150	Roadside
15	Ningnan County (27°2′13″ N, 102°45′26″ E)	938	Roadside
16	Xichang City (27°47′46″ N, 102°19′29″ E)	1530	Forest land
17	Xichang City (27°56′41″ N, 102°12′6″ E)	1500	Grass land
18	Xichang City (27°59′0″ N, 102°11′29″ E)	1510	Forest land
19	Xichang City (28°5′26″ N, 102°10′57″ E)	1560	Ditch side
20	Ningnan County (27°3′48″ N, 102°45′57″ E)	1250	Roadside
21	Mianning County (28°16′37″ N, 102°10′52″ E)	1600	Farmland
22	Huidong County (26°31′43″ N, 102°30′37″ E)	2130	Forest land
23	Huili County (26°41′41″ N, 102°13′52″ E)	1858	Farmland
24	Huili County (26°41′37″ N, 102°13′53″ E)	1842	Farmland
25	Huili County (26°52′42″ N, 102°17′1″ E)	2080	Forest land
26	Dechang County (27°27′48″ N, 102°10′51″ E)	1370	River side
27	Dechang County (27°25′44″ N, 102°12′15″ E)	1485	Roadside
28	Dechang County (27°18′3″ N, 102°20′1″ E)	1350	Roadside
29	Dechang County (27°39′45″ N, 102°11′39″ E)	1428	Roadside
30	Puge County (27°43′38″ N, 102°14′15″ E)	1500	Roadside
31	Ningnan County (27°5′0″ N, 102°43′47″ E)	1120	Reservoir side
32	Xichang City (27°59′54″ N, 102°11′14″ E)	1560	Railway side
33	Mianning County(28°32′17″ N, 102°10′52″ E)	1725	Roadside
34	Huili County (26°49′43″ N, 102°16′50″ E)	2070	Farmland
35	Dechang County (27°26′40″ N, 102°11′16″ E)	1435	Forest land
36	Dechang County (27°11′59″ N, 102°17′21″ E)	1175	Roadside
37	Ningnan County (27°4′48″ N, 102°43′43″ E)	1230	Roadside
38	Huili County (27°0′46″ N, 102°15′42″ E)	1447	Roadside
39	Xichang City (28°10′27″ N, 102°10′24″ E)	1590	Roadside
40	Mianning County (28°25′7″ N, 102°10′49″ E)	1670	Rare earth mining area
41	Dechang County (27°27′25″ N, 102°11′1″ E)	1450	Waste cinder yard
42	Mianning County (28°32′44″ N, 102°11′33″ E)	1750	Area near Pb-Zn mine

Table S2 N, P, and K in *A. adenophora* plant, and TN, TP, and TK in rhizosphere and non-rhizosphere soils (g/kg).

Site No.	pH	Soil texture	Plant			Rhizosphere soil			No-rhizosphere soil		
			N	P	K	TN	TP	TK	TN	TP	TK
1	7.94	Sandy clay	8.49	3.52	13.36	0.88	0.31	22.72	1.06	0.30	22.41
2	8.26	Loam	6.85	1.73	10.20	1.87	0.23	10.84	1.55	0.33	9.57
3	8.10	Sandy clay	8.19	2.76	9.30	2.18	0.66	26.51	1.07	0.78	24.55
4	7.99	Sandy clay	6.72	1.98	10.94	0.82	0.69	20.75	0.41	0.61	25.84
5	7.77	Loam	11.25	3.15	15.58	0.19	0.51	22.76	0.13	0.33	21.98
6	5.96	Sandy clay	4.77	1.29	8.80	2.25	0.99	22.53	2.01	0.98	21.95
7	8.49	Sandy loam	6.61	2.19	8.94	1.82	0.99	16.44	2.10	0.98	14.59
8	7.11	Sandy clay	11.72	3.98	17.65	2.70	0.21	21.80	1.91	1.00	20.81
9	7.98	Loam	9.86	4.36	13.40	1.46	0.24	12.58	0.56	0.12	15.67
10	8.04	Sandy clay	12.91	4.18	14.65	0.40	0.30	14.07	0.37	0.26	12.05
11	8.27	Sandy loam	6.93	2.10	8.68	0.39	0.95	21.24	0.58	0.45	19.63
12	5.00	Loam	9.89	1.08	12.70	2.06	0.73	8.41	1.18	1.00	8.36
13	8.30	Clay loam	7.90	3.42	11.31	2.57	0.48	17.12	1.07	0.37	21.73
14	7.85	Clay loam	12.71	4.96	12.36	2.19	0.55	22.42	1.09	0.27	27.97
15	8.40	Loam	10.89	3.26	11.54	0.86	0.27	28.13	0.29	0.08	28.01
16	8.42	Sandy loam	5.93	3.02	10.52	0.93	0.18	23.00	0.66	0.22	21.08
17	8.01	Loam	13.84	4.71	11.16	2.20	0.75	17.81	0.86	0.53	19.58
18	8.00	Loam	10.18	4.23	14.33	0.77	0.12	29.17	0.81	0.47	26.43
19	7.74	Loam	8.95	1.85	8.13	0.95	1.24	19.60	0.97	1.45	17.99
20	8.29	Loam	10.40	1.96	13.18	0.44	0.48	23.76	0.21	0.44	24.02
21	7.54	Sand	6.91	1.99	10.28	1.82	1.09	16.82	2.39	1.11	13.69
22	7.04	Clay loam	4.59	0.71	7.52	3.62	0.80	21.93	3.31	0.81	25.28
23	5.83	Clay loam	8.14	1.80	8.52	1.99	0.56	19.94	1.82	0.72	19.67
24	6.45	Clay loam	11.38	4.37	15.39	1.00	0.28	25.37	0.57	0.20	20.62
25	7.87	Clay loam	7.36	2.97	10.57	0.89	0.36	17.49	0.83	0.29	15.55
26	6.23	Clay loam	12.50	5.46	16.76	3.14	1.08	20.60	0.63	1.81	34.46
27	4.62	Clay loam	5.64	1.17	7.45	0.74	1.24	22.50	0.38	0.64	28.93
28	6.85	Clay loam	9.35	4.04	11.42	1.41	0.77	11.92	0.84	0.78	12.04
29	7.27	Clay loam	14.36	3.10	13.12	2.39	2.83	18.03	2.37	1.52	24.42
30	7.87	Clay loam	6.78	0.87	10.22	0.83	0.39	32.46	0.80	0.36	24.90
31	8.29	Clay	6.89	3.99	9.52	0.66	2.75	34.93	0.51	2.47	24.61
32	8.28	Clay loam	6.58	1.39	7.44	1.36	0.27	8.25	0.49	0.28	13.71
33	7.96	Clay loam	12.77	2.21	12.91	0.78	0.50	15.01	0.53	0.41	16.70
34	5.23	Clay loam	11.86	2.53	17.25	0.85	0.66	13.07	0.53	0.38	9.53
35	8.09	Sandy loam	15.09	5.25	14.60	2.19	0.66	14.42	0.68	0.35	14.76
36	8.20	Sandy loam	5.36	1.98	7.72	2.04	0.31	14.41	1.30	0.24	19.21
37	7.85	Clay loam	13.57	3.57	13.60	1.91	0.81	19.67	1.29	0.80	19.52
38	8.04	Clay loam	6.62	3.78	9.89	1.01	0.62	25.74	0.73	0.57	28.10
39	8.00	Loam	11.10	1.94	13.08	2.66	0.93	22.06	0.93	0.70	22.19
40	8.27	Clay loam	8.11	2.08	11.96	0.77	0.35	30.88	0.62	0.36	32.17
41	5.12	Loam	12.78	2.17	11.97	1.59	0.98	18.69	1.09	1.00	19.51
42	7.72	Sand	10.88	3.86	12.32	0.98	0.48	9.53	0.55	0.34	9.45
Range	5.00–8.49	–	4.59–15.09	0.71–5.46	7.44–17.65	0.19–3.62	0.12–2.83	8.25–34.93	0.13–3.31	0.08–2.47	8.36–34.46
Mean	7.61	–	9.28	2.88	11.67	1.49	0.71	19.89	1.00	0.65	20.31
CV (%)	11.85	–	31.19	43.74	23.36	55.27	79.56	31.66	67.75	75.31	31.11

N, P, and K represent nitrogen, phosphorus, and potassium in *A. adenophora* plant; TN, TP, and TK represent total nitrogen, total phosphorus, and total potassium in the soil; CV represents variation coefficient.

Table S3 Contents of SOC, AN, AP, and AK in rhizosphere and non-rhizosphere soil ($n = 42$).

Indicator	Range		Mean		CV (%)	
	Rhizosphere	Non-rhizosphere	Rhizosphere	Non-rhizosphere	Rhizosphere	Non-rhizosphere
SOC (g/kg)	1.77–128.58	0.50–97.54	24.38[a]	15.02[b]	92.30	109.72
AN (mg/kg)	11.22–161.75	7.33–198.75	70.83[a]	51.92[b]	58.44	79.61
AP (mg/kg)	1.41–65.20	2.52–63.92	22.95[a]	21.37[a]	69.60	75.68
AK (mg/kg)	36.74–398.76	15.54–385.99	163.94[a]	110.95[b]	56.64	83.43

SOC, AN, AP, and AK represent soluble organic carbon, alkali-hydrolysable nitrogen, available phosphorus, and available potassium in *A. adenophora* growing soil, respectively. CV represents variation coefficient. Different letters in the same column indicate the significance of difference at $p < 0.05$ level.

Table S4 Correlation analysis between nutrient contents of *A. adenophora* and soil nutrient conditions ($n = 42$).

Plant nutrient	OM	TN	TP	TK	AN	AP	AK
Non-rhizosphere soil							
N	0.090	0.452**	0.157	0.182	0.655**	0.287	0.360*
P	0.278	0.292	0.446**	0.091	0.233	0.324*	0.391*
K	0.084	0.182	0.104	0.026	0.222	0.175	0.534**
Rhizosphere soil							
N	−0.017	0.247	0.096	0.167	0.207	0.215	0.377*
P	0.146	0.081	0.449**	0.142	0.001	0.533**	0.361*
K	−0.010	0.174	0.035	0.049	0.148	0.103	0.502**

* and ** indicate $p < 0.05$ and $p < 0.01$ significant levels, respectively. N, P, and K represent nitrogen, phosphorus, and potassium in *A. adenophora* plant; OM, TN, TP, TK, AN, AP, and AK represent organic matter, total nitrogen, total phosphorus, total potassium, alkali-hydrolysable nitrogen, available phosphorus, and available potassium in *A. adenophora* growing soil.