Changes in Cucumber Rhizosphere *Bacillus* spp. Abundance and Community Structure During Long-Term Continuous Monocropping

Muhammad Khashi u Rahman\textsuperscript{1,2}, Changli Ma\textsuperscript{1,2}, Fengzhi Wu\textsuperscript{1,2*}, Xingang Zhou\textsuperscript{1,2**}

\textsuperscript{1}Key Laboratory of Biology and Genetic Improvement of Horticultural Crops (Northeast Region), Ministry of Agriculture and Rural Affairs, Northeast Agricultural University, Harbin, China
\textsuperscript{2}College of Horticulture and Landscape Architecture, Northeast Agricultural University, Harbin, China

*Received: 12 January 2020
Accepted: 2 April 2020

Abstract

Continuous monocropping has been a traditional way of cropping system in most parts of the world. It is important to study its effects on soil microbial communities, which are an important element of any agroecosystem functioning and for both plant and soil health. In this study, we used real-time PCR and PCR-denaturing gel electrophoresis (PCR-DGGE) techniques to analyze changes in *Bacillus* spp. abundance, diversity and community structure in continuously monocropped cucumber (*Cucumis sativus* L.) rhizosphere during nine cropping seasons (after every 2 seasons i.e. 1, 3, 5, 7, 9). Results showed that continuous monocropping significantly changed the *Bacillus* spp. abundance, diversity and community structure, and the effect was in course of time. The abundance of *Bacillus* spp. increased up to 5\textsuperscript{th} cropping season and then decreased in following cropping seasons. The number of DGGE bands, Shannon-Wiener Index and Evenness indexes decreased during 3\textsuperscript{rd} cropping season and, after that, increasing trend was observed up to 9\textsuperscript{th} cropping season. These results suggest that the diversity of crop specific *Bacillus* spp. might start increasing but overall abundance of those keep decreasing after a specific period of time during long-term cucumber continuous monocropping.

Keywords: allelopathy, bacterial community, plant-microbe interaction, soil sickness

Introduction

To meet the increasing demand of food for the growing world population, it is necessary to take timely measures through sustainable improvement of agricultural productivity [1]. Sustainable agriculture is not all about producing high output crops in short period of time, but rather developing and maintaining a healthy environment for handsome production [2]. For that, land management practices disproportionately impact on soil functioning and agricultural productivity [3]. Studies have shown that selection of proper cropping system (i.e. intercropping, crop rotation, cover crops) could maintain soil organic C, facilitate biological functioning and improve overall soil physical properties [4-6]. In contrary, when we the grow the same crop on the same piece of land repeatedly, it causes accumulation...
Multiple species of Bacillus occur abundantly in most of the rhizosphere soils [17]. In many areas, the overall yield of cucumber (Cucumis sativus L.) has been decreased because of continuous monocropping system [25]. One of the explanations for this could be that continuous monocropping have found to be affecting negatively on rhizosphere Bacillus spp. in several crops [8, 9, 19]. However, long-term effects of continuous monocropped cucumber have yet to be disclose.

Since most of the past studies were conducted on single or few monocropping seasons, it would be interesting to investigate long-term effects of cucumber monocropping on rhizosphere Bacillus spp. community. To understand the mechanism of changes in certain microbial community, we monitored Bacillus spp. community in rhizosphere of continuously monocropped cucumber for nine cropping seasons with the aim to analyze how its abundance, diversity and community structure affected by long-term continuous monocropping. We hypothesized that (1) long-term continuous monocropping will negatively affect Bacillus spp. abundance, diversity and community structure, and (2) this effect will be duration dependent.

Materials and Methods

Plant Material and Greenhouse Experiment

Cucumber Jinlv 3, which is a famous cultivar in northeast China, was used in a pot experiment conducted from April 2005 to April 2009 in a greenhouse located in the Horticulture Experimental Station in Northeast Agricultural University, Harbin, China (45°41′N, 126°37′E). Each year, cucumber was cultivated twice (April-July, July-October). Each pot contained 8 kg of soil, which was collected (for first cropping season) from the upper layer of grass covered open field in the same Horticulture Experimental Station, undisturbed for ≥15 years. The soil used in experiment was black soil with sandy loam texture, containing available N: 89.02 mg kg⁻¹; available P: 63.36 mg kg⁻¹; available K: 119.15 mg kg⁻¹; organic matter: 3.67%, and with EC (1:2.5, w/v), 0.33mS cm⁻¹; and pH (1:2.5, w/v), 7.78.

Before germinated in dark at 28°C, cucumber seeds were sterilized with 2.5% NaClO for 10 minutes and washed thoroughly with distilled water. Germinated seedlings were then transplanted at four true leaves stage to experimental pots (one seedling per pot) on April 25 and July 25 of each year for each cropping seasons. After completion of first experiment, soil was kept in pots to use for following season experiment, up to 9th cropping. Each cropping season contained a total of 60 pots which were placed randomly in the greenhouse. Fertilizers were applied according to traditional recommendation with decomposed swine manure (organic matter: 15%; N: 0.5%; P: 0.5%; K: 0.4%). For top-dressing, urea fertilizer (N: 46%) was used at the rate of 25 g per pot after 30 days of transplantation. Ground water was applied twice a week to maintain proper suitable moisture of 55±2 of water holding capacity and weeds were removed manually.

Sample Collection and DNA Extraction

The soil samples were collected from five plants for each replicate as previously described by Zhou et al. [20] three times (on 30, 40 and 50 days of transplanting). Collected samples were promptly stored at -70°C for soil microbial DNA extraction. DNA was extracted using the PowerSoil Kit (MO BIO Laboratories, Inc., Carlsbad, CA, USA). The amount and purity of extracted DNA was estimated spectrophotometrically by measuring the optical density at 260 and 280 nm, and DNA was stored at -20°C for further analysis.

PCR-DGGE Analysis

The community structure of Bacillus spp. was estimated through PCR-DGGE analysis. PCR amplification for Bacillus spp. was carried out using nested primer sets BacF/BacR and F338GC/R518 as previously described by Zhou et al. [9]. The PCR conditions were: 95°C for 5 min followed by 28 cycles of 95°C for 30s, 56°C for 45s, 72°C for 90s, and final extension at 72°C for 10 min. For DGGE analysis, 6% (w/v) acrylamide gel with 56-60% denaturing gradient was used. A 1xTAE (Tris-acetate-EDTA) buffer was used for running gel for 14 h under conditions of 60°C and 80 V with a Dcode universal mutation detection
Changes in Cucumber Rhizosphere Bacillus spp.

system (Bio-Rad Lab, LA, USA). Gel was stained in 1:3300 (v/v) GelRed (Biotium, USA) nucleic acid staining solution promptly after electrophoresis. Finally, an AlphalImager HP imaging system (Alpha Innotech Corp., CA, USA) was used to photograph the DGGE profiles under UV light.

Real-Time PCR Assay

To estimate total abundance of Bacillus spp., a real-time PCR assay was carried out using primer set of BacF/BacR as described earlier [9]. The protocol set in the assay was: 95°C for 5 min; followed by 30 cycles of 95°C for 30s, 65°C for 30s and 72°C for 90s; and finally, an extension at 72°C for 10 min. A dilution series (10²-10⁵) of plasmid DNA containing Bacillus spp. 16S rRNA genes was used to develop a standard curve. For negative control, sterilized water was used to replace the template. Amplification of each replicate was done in triplicate. To confirm the specificity of the product, melting curve analysis and agarose gel electrophoresis were used. The initial copy number of target gene were determined by comparing obtained threshold cycle (Ct) value of each sample with standard curve.

Statistical Analysis

For the analysis of DGGE profiles banding patterns, the Quantity One v4.5 (Bio-Rad Lab, LA, USA) was used. To compare the banding pattern between the samples, principle component analysis (PCA) was used with Canoco for Windows 4.5 software (Plant Research International, Wageningen, the Netherlands). The Bacillus spp. community diversity parameter including number of bands, Shannon-Wiener and evenness indexes were calculated as described previously by Zhou et al. [20]. Data was analyzed by analysis of variance (ANOVA), and the mean values between treatments for Bacillus spp. diversity parameters were compared using Tukey’s honestly significant difference (HSD) test at probability level of <0.05.

Results and Discussion

The soil functioning carried out by microbial communities mainly decides the productivity and sustainability of agriculture system [21]. It is well understood now that agricultural practices such as tillage, fertilization and cropping system could

Fig. 1. Changes in Bacillus spp. community abundance a), and diversity parameters including no. of DGGE bands b), Shannon-Wiener c) and evenness d) indexes during different cropping seasons. The values of each season in particular figure labeled with different letter are significantly different (P<0.05; Tukey’s HSD test).
Rahman M.K., et al.

significantly influence changes in soil microbial community [20, 22]. In this study, we used real-time PCR and PCR-denaturing gel electrophoresis (PCR-DGGE) techniques to monitor the changes in Bacillus spp. community abundance, diversity and structure in cucumber rhizosphere during pot experiments for 9 cropping seasons.

Changes in Bacillus spp. Community Abundance and Diversity

Real-time PCR analysis showed a significant difference in Bacillus spp. abundance between 1st, 3rd and 5th cropping seasons, while there was no difference found between abundance during season 1, 7 and 9 of continuous monocropping (Fig. 1a). The highest abundance was examined during 5th cropping season followed by 3rd cropping season, while the Bacillus spp. community was lowest during 1st, 7th and 9th seasons among all 9 monitored cropping seasons. Our results showed an increasing trend in Bacillus spp. abundance in the beginning up to 5th cropping season, however, it decreased gradually to 1st cropping season at the end of experiment. The abundance of Bacillus spp. was lowest during first cropping season and reached to the highest value during 5th cropping season among all examined 9 cropping seasons. In contrary, DGGE analysis revealed that continuously monocropping did significantly affect number of bands (Fig. 1b), Shannon-Wiener (Fig. 1c) and evenness (Fig. 1d) indexes of samples from 1st, 3rd and rest of cropping seasons (P<0.05). The highest number of bands were found during 1st and 9th followed by 7th and 5th cropping season, respectively, while least were during 3rd cropping season. Almost the same trend was seen in Shannon-Wiener and evenness indexes of Bacillus spp. diversity parameters. These results of diversity parameters showed that the diversity of Bacillus spp. decreased until 3rd cropping season but increased afterward to 1st cropping season at 9th cropping season.

When same crop is grown again and again on same piece of land, the autotoxins released through root exudates and from plant debris start accumulate in root zone [23, 24]. An increasing number of studies have shown that the accumulation of plant released phenolic compounds due to continuous monocropping and exogenously applied autotoxins can alter the composition of soil microbial communities [25-29] including plant beneficial soil microbial species such as Bacillus spp. [30-32]. According to Zhou and Wu [33], vanillic acid significantly reduced abundance and changed community structure of Bacillus spp. during cucumber monocropping. Similarly, another autotoxin compound, vanillin, adversely affected Bacillus spp. community composition in cucumber rhizosphere soil [31]. Soil assembled autotoxin compounds can also damage plant roots and increase ion leakage rate and affect rhizosphere microbial communities [34]. In this study, the decreasing trend in Bacillus spp. abundance after 5th cropping season could be due to increase in higher accumulation of cucumber autotoxins in soil with increase in number of cropping seasons. For example, Li et al. [35] found that the accumulation of autotoxin i.e. p-hydroxybenzoic acid, ferulic acid, cinnamic acid and p-coumaric acid increased with increase in number of monocropping seasons of strawberry. Concerning the contrary results of Bacillus spp. diversity parameters, one can assume that growing same crop consistently without introduction of new crop might increase abundance of crop-specific bacterial strains resulting an increase in Bacillus spp. diversity with increase in number of cropping seasons.

Changes in Bacillus spp. Community Structure

The DGGE analysis showed an obvious visual difference in banding pattern of Bacillus spp. among 9 cropping seasons. Capital letters in diagrams indicate the no of cropping season as A: 1, B: 3, C: 5, D: 7, E: 9.
cropping seasons (Fig. 2a). PCA analysis showed that continuously monocropped cucumber totally changed Bacillus spp. community structure during 9 consecutive cropping seasons as separated samples can be seen in Fig. 2b. PCA plot of DGGE banding pattern of Bacillus spp. explained 58.8% and 12.4% in first and 2nd PCA axis, respectively. In particular, the difference between 3rd and 5th cropping season with the rest of cropping seasons was more obvious. It has examined that several factors, such as crop type, cropping system, tillage management and plant growth stage, could significantly affect rhizosphere microbial communities [27, 36]. Among these factors, cropping system is one of the key factors which could potentially affect soil microbial structure [37]. Similarly, in our study, PCA analysis can distinguish Bacillus spp. community structure in rhizosphere samples taken from different cropping seasons (Fig. 2b). This might be due to different root exudation pattern, because root exudates are the main derivers for rhizosphere microbial compositions [38]. Another possible reason could be the accumulation of autoxotoxins in potting soil after regular cucumber monocropping. The phenolic acids are revealed to greatly affect soil bacterial community structure in previous studies [31, 39]. For example, the community structure of Bacillus spp. was comprehensively altered by exogenously application of phenolic compounds [33].

Conclusion

Long-term monocropping of cucumber could decrease rhizosphere Bacillus spp. community abundance and changing community structure. From these results, we speculate that the accumulation level of autoxotoxins with long-term and constantly planting cucumber increased which resulted in lowering the abundance and changing in community structure of Bacillus spp. with increase in number of cropping seasons. This study has provided us great insights that how long-term continuously monocropping could affect plant beneficial microbial genre such as Bacillus spp.

Acknowledgment

This work was supported by the the Natural Science Foundation of Heilongjiang Province (YQ2019C009), National Natural Science Foundation of China (31772361), China Agricultural Research System (CARS-23-B-10), and Longjiang Scholars Program (Q201920).

Conflict of Interest

The authors declare no conflict of interest to disclose.

References

1. CALICIIOGLU O., FLAMMINI A., BRACCO S., BELLÜ L., SIMS R. The future challenges of food and agriculture: An integrated analysis of trends and solutions. Sustainability, 11 (1), 222. 2019.
2. WALL P.C. Tailoring conservation agriculture to the needs of small farmers in developing countries: an analysis of issues. J. Crop Improv., 19 (1-2), 137. 2007.
3. POWLSON D.S., GREGORY P.J., WHALLEY W.R., QUINTON J.N., HOPKINS D.W., WHITMORE A.P., WHALLEY W.R., HIRSCH P.R. GOULDING K.W. Soil management in relation to sustainable agriculture and ecosystem services. Food policy, 36. S72-S87. 2011.
4. MALÉZIEUX E., CROZAT Y., DUPRAZ C., LAURANS M., DE TOURDONNET S., CALDERÓN K., SPOR A., BRACCO S., MAKOWSKI D., OZIER-LAFONTAINE H., RAPIDEL B., DE TOURDONNET S., VALANTIN-MORISON M. Mixing plant species in cropping systems: concepts, tools and models: a review. In Sustainable Agriculture. Springer, Dordrecht, 329-. 2009
5. ARSHAD M., NAWAZ R., AHMAD S., SHAH G.A., FAIZ F., AHMAD N., IRSHAD M.A., RANAMUKHAARACHCHI S.L. Growth, Yield and Nutritional Performance of Sweet Sorghum and Legumes in Sole and Intercropping Influenced by Type of Legume, Nitrogen Level and Air Quality. Pol. J. Environ. Stud., 29 (1), 533. 2019.
6. JIN X., ZHANG J., SHI Y., WU F., ZHOU X. Green manures of Indian mustard and wild rocket enhance cucumber resistance to fusarium wilt through modulating rhizosphere bacterial community composition. Plant Soil, 441 (1-2), 283. 2019.
7. ZHOU X., GAO D., LIU J., QIAO P., ZHOU X., LU H., WU X., LIU D., JIN X., WU F. Changes in rhizosphere soil microbial communities in a continuously monocropped cucumber (Cucumis sativus L.) system. Eur. J. Soil Biol., 60, 1. 2014.
8. LING N., DENG K., SONG Y., WU Y., ZHAO J., RAZA W., HUANG Q., SHEN Q. Variation of rhizosphere bacterial community in watermelon continuous monocropping soil by long-term application of a novel bioorganic fertilizer. Microbiol. Res., 169 (7-8), 570. 2014.
9. ZHOU X., GAO D., ZHAO M., ZHANG J., LI L., WU F. Dynamics of soil bacterial communities in Jerusalem artichoke monocropping system. Allelopathy J., 39, 167. 2016.
10. CESARANO G., ZOTTI M., ANTIGNANI V., MARRA R., SCALA F., BONANOMI G. Soil sickness and negative plant-soil feedback: A reappraisal of hypotheses. J. Plant Pathol., 99 (3), 545. 2017.
11. CALDERÓN K., SPOR A., BREUIL M.C., BRU D., BIZOUARD F., VIOLLE C., BARNARD R.L., PHILIPPOT L. Effectiveness of ecological rescue for altered soil microbial communities and functions. ISME J., 11 (1), 272. 2017.
12. LIU L., WANG Y., GAI Z., LIU D., WU P., WANG B., ZOU C., LI C., YANG F. Responses of soil microorganisms and enzymatic activities to alkaline stress in sugar beet rhizosphere. Pol. J. Environ. Stud., 29 (1), 739. 2019.
13. WALDROP M.P., FIRESTONE M.K. Response of small farmers in developing countries: an analysis of measures. Food policy, 11. S72-S87. 2011.
14. BOUZOUIMITA A., METOUJI M., JEMNI M., KABAEIR N., BELHOUCHETTE K., FERCHICHI A. The efficacy of various bacterial organisms for biocontrol of fusarium...
root rot of olive in Tunisia. Pol. J. Environ. Stud., 29 (1), 11, 2020.
15. SINGH J.S., GUPTA V.K. Soil microbial biomass: a key soil driver in management of ecosystem functioning. Sci. Total Environ., 634, 497. 2018.
16. BENDER S.F., WAGG C. VAN DER HEIJDEN M.G. An underground revolution: biodiversity and soil ecological engineering for agricultural sustainability. Trends Ecol. Evol., 31 (6), 440. 2016.
17. GOVINDASAMY V., SENTHILKUMAR M., MAGHESHWARAN V., KUMAR U., BOSE P., SHARMA V., ANNAAPURNA K. Bacillus and Paenibacillus spp.: potential PGPR for sustainable agriculture. In Plant growth and health promoting bacteria. Springer, Berlin, Heidelberg, 333, 2010.
18. VAN LOON L.C. Plant responses to plant growth-promoting rhizobacteria. In New perspectives and approaches in plant growth-promoting Rhizobacteria research. Springer, Dordrecht. 243, 2007.
19. SANGUIN H., SARNIGUET A., GAZENGEL K., GRUNDMANN G.L. Rhizosphere bacterial communities associated with disease suppressiveness stages of take-all decline in wheat monoculture. New Phytol., 184 (3), 694, 2009.
20. ZHOU X., YU G., WU F. Effects of intercropping cucumber with onion or garlic on soil enzyme activities, microbial communities and cucumber yield. Eur. J. Soil Biol., 47 (5), 279, 2011.
21. BEVER J.D., PLATT T.G., MORTON E.R. Microbial population and community dynamics on plant roots and their feedbacks on plant communities. Annu. Rev. Microb., 66, 265, 2012.
22. GARBEVA P., VAN ELSAS J.D., VAN VEE N.J.A. Rhizosphere microbial community and its response to plant species and soil history. Plant soil, 302 (1-2), 19, 2008.
23. ZHOU X., WU F. p-Coumaric acid influenced cucumber rhizosphere soil microbial communities and the growth of Fusarium oxysporum f. sp. cucumerinum Owen. PloS one, 7 (10), e48288, 2012.
24. TIAN Y., FENG F., ZHANG B., LI M., WANG F., GU L., CHEN A., LI Z., SHAN W., WANG X., CHEN X. Transcriptome analysis reveals metabolic alteration due to consecutive monoculture and abiotic stress stimuli in Rehamannia glutinosa Libosch. Plant Cell Rep., 36 (6), 859, 2017.
25. ZHOU X., LIU J., WU F. Soil microbial communities in cucumber monoculture and rotation systems and their feedback effects on cucumber seedling growth. Plant Soil, 415 (1-2), 507, 2017.
26. ZHAO Q., XIONG W., XING Y., SUN Y., LIN X., DONG, Y. Long-term coffee monoculture alters soil chemical properties and microbial communities. Sci. Rep., 8 (1), 6116, 2018.
27. ZHOU X.G., WANG J., JIN X., LI D.L., SHI Y.J., WU, F.Z. Effects of selected cucumber root exudates components on soil Trichoderma spp. communities. Allelopathy J., 47 (2), 257, 2019.
28. JIA H.T., LIU J.Y., SHI Y.J., LI D.L., WU F.Z., ZHOU X.G. Characterization of cucumber rhizosphere bacterial community with high-throughput amplicon sequencing. Allelopathy J., 47 (1), 103, 2019.
29. JIN X., WU F., ZHOU X. Different toxic effects of ferulic and p-hydroxybenzoic acids on cucumber seedling growth were related to their different influences on rhizosphere microbial composition. Biol. Fertil. Soils, 56 (1), 125, 2020.
30. JIA H.T., CHEN S.C., YANG S.Y., SHEN Y.H., QIAO P.L., WU F.Z., ZHOU X.G. Effects of vanillin on cucumber rhizosphere bacterial community. Allelopathy J., 44 (2), 191, 2018.
31. ZHOU X.G., WANG Z.L., PAN D.D., WU F.Z. Effects of vanillin on cucumber (Cucumis sativus L.) seedling rhizosphere Bacillus and Pseudomonas spp. community structures. Allelopathy J., 44 (2), 255, 2018.
32. KHASHI U RAHMAN M., ZHOU X.G., WU F.Z. The role of root exudates, CMNs, and VOCs in plant–plant interaction. J. Plant Interact., 14 (1), 630, 2019.
33. ZHOU X., WU F. Vanillic acid changed cucumber (Cucumis sativus L.) seedling rhizosphere total bacterial, Pseudomonas and Bacillus spp. communities. Sci. Rep., 8 (1), 4929, 2018.
34. YU J.Q., MATSUI Y. Effects of root exudates of cucumber (Cucumis sativus) and allelochemicals onion uptake by cucumber seedlings. J. Chem. Ecol., 23 (3), 817, 1997.
35. LI X., LEWIS E.E., LIU Q., LI H., BAI C., WANG, Y. Effects of long-term continuous cropping on soil nematode community and soil condition associated with replant problem in strawberry habitat. Sci. Rep., 6 (1), 30466, 2016.
36. DU Y., WANG G., JIN J., LIU J., ZHANG Q., LIU, X. Bacterial communities in soybean rhizosphere in response to soil type, soybean genotype, and their growth stage. Soil Biol. Biochem., 41 (5), 919, 2009.
37. ASHWORTH A.J., DEBRYN J.M., ALLEN F.L., RADOSEVICH M., OWENS P.R. Microbial community structure is affected by cropping sequences and poultry litter under long-term no-tillage. Soil Biol. Biochem., 114, 210, 2017.
38. SASSE J., MARTINOIA E., NORTHEN T. Feed your friends: do plant exudates shape the root microbiome?. Trends Plant Sci., 23 (1) 25, 2018.
39. QU X.H., WANG J.G. Effect of amendments with different phenolic acids on soil microbial biomass, activity, and community diversity. Appl. Soil Ecol., 39 (2), 172, 2008.