Supplementary Information

Threshold conditions for the accumulation of microbial residues in terrestrial ecosystems

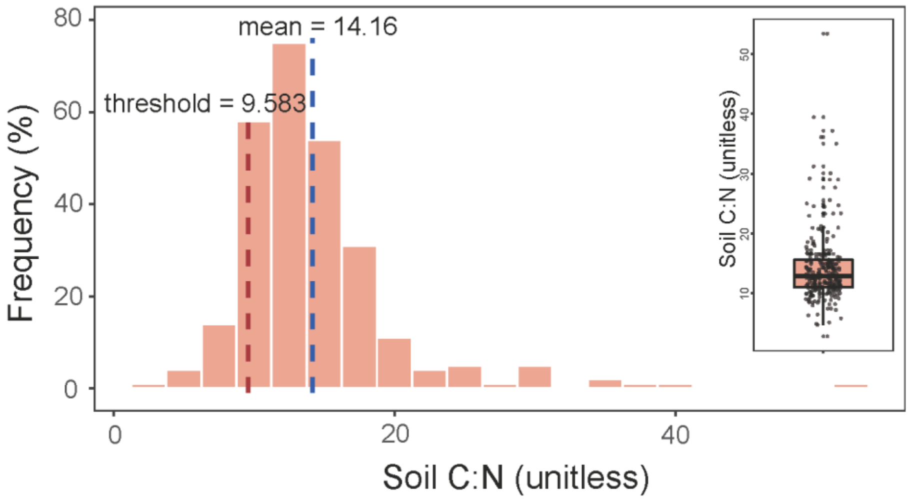
This file includes:

Supplementary Figures: 5

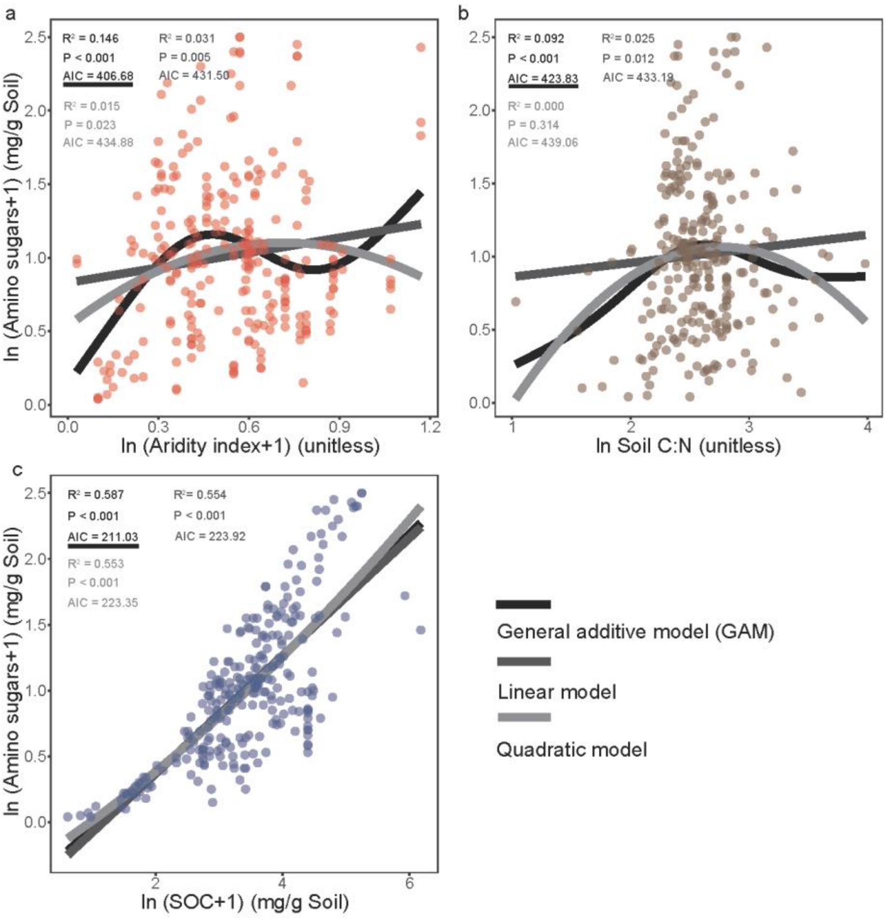
Supplementary Table: 1

Supplementary References

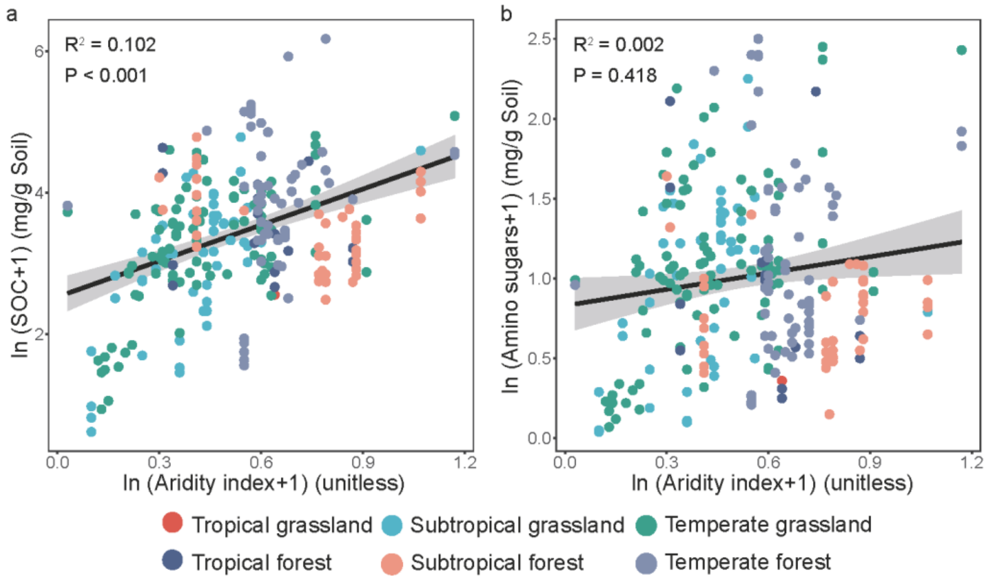
Supplementary Data in supplementary Excel



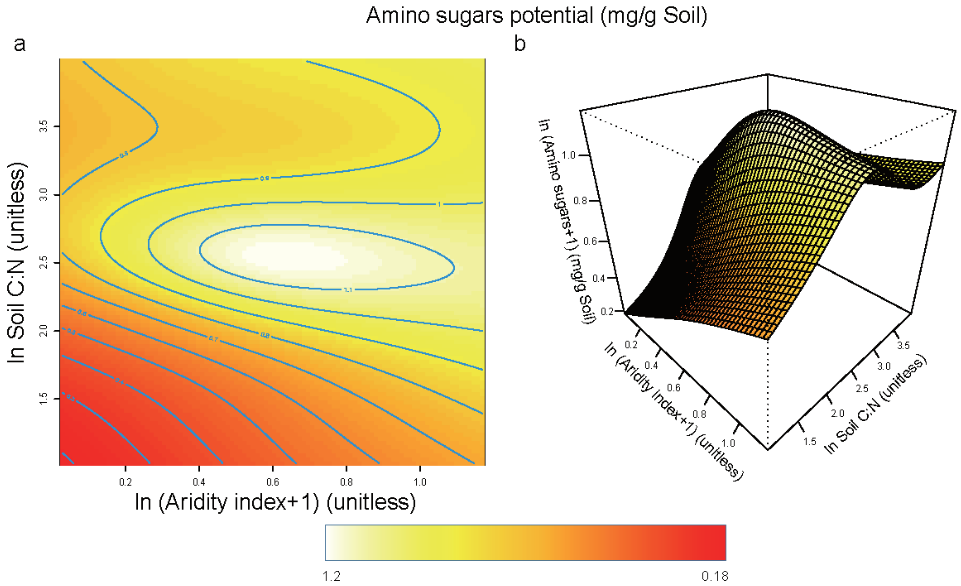
Supplementary Figure 1 Frequency distribution histogram of the original data of soil C:N ratio. The box graph in the upper right corner and the light black jitter scatter show the distribution of data. The blue dotted line in the figure represents the mean value of soil C:N ratio, and the red dotted line represents the threshold of microbial residue with the increase in soil C/N ratio. The numbers represent the mean value and threshold value, respectively.



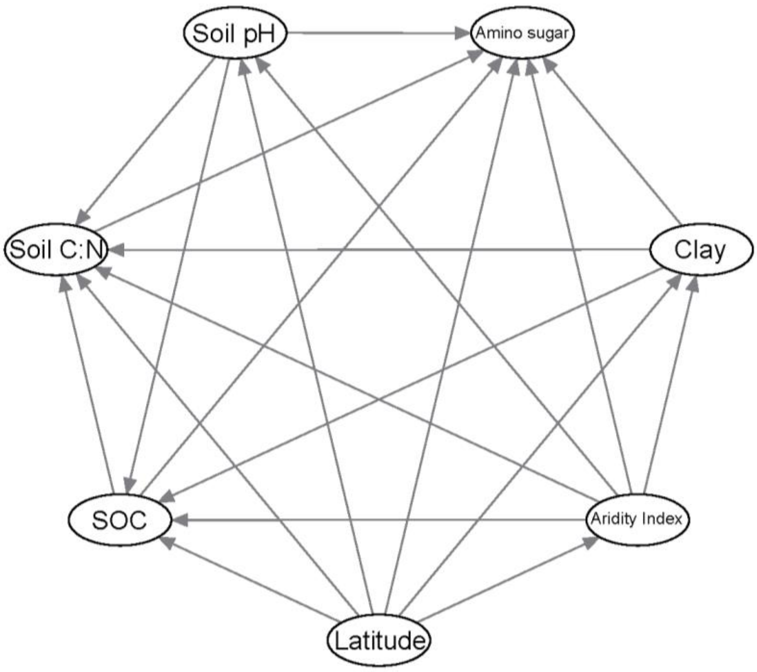
Supplementary Figure 2 The best model of the response of soil microbial residues to various environmental variables. In the figure, the black curves represent the fit of the GAM, the dark gray line represents that of the linear model, and the light gray curve represents that of the quadratic model. Akaike information criteria (AIC) are used to assess the fit the linear and nonlinear models such that best fitting models have lower AIC values. Black lines are used to indicate the AIC value of the best model and R^2 and P values of each model are provided. GAM: general additive model.



Supplementary Figure 3 Linear regression of aridity index with soil organic carbon (SOC) and amino sugar (b). The data are logarithmically transformed. Points with different colors represent different plot types. The values of R^2 and P indicate the correlation coefficient and significance of linear regression, respectively.



Supplementary Figure 4 Increases in soil amino sugar value with aridity degree and soil nutrients. The data of each variable are logarithmically transformed. The data showed an increasing trend with a clear threshold of aridity index at 0.57 and a threshold of soil C:N ratio at 2.26, where the value of soil amino sugar changed significantly from high to low.



Supplementary Figure 5 Prior structural equation model (SEM) of amino sugar. The direction of the arrow indicates the causal relationship between variables, which is based on existing knowledge and the correlation in Figure 2b. SOC: soil organic carbon.

Supplementary Table 1 The generalized climate classification scheme for Aridity Index values (UNEP 1997)

Aridity Index Value	Climate Class
< 0.03	Hyper Arid
0.03 – 0.2	Arid
0.2 – 0.5	Semi-Arid
0.5 – 0.65	Dry sub-humid
> 0.65	Humid

Supplementary References: Studies included in this meta-analysis

1 Yang, L. *et al.* Decline in the contribution of microbial residues to soil organic carbon along a subtropical elevation gradient. *Science of The Total Environment* **749**, 141583, doi:https://doi.org/10.1016/j.scitotenv.2020.141583 (2020).

2 Chen, J., Ji, C., Fang, J., He, H. & Zhu, B. Dynamics of microbial residues control the responses of mineral-associated soil organic carbon to N addition in two temperate forests. *Science of The Total Environment* **748**, 141318, doi:https://doi.org/10.1016/j.scitotenv.2020.141318 (2020).

3 Fan, Y. *et al.* N addition increased microbial residual carbon by altering soil P availability and microbial composition in a subtropical Castanopsis forest. *Geoderma* **375**, 114470, doi:https://doi.org/10.1016/j.geoderma.2020.114470 (2020).

4 Ma, S. *et al.* Effects of seven-year nitrogen and phosphorus additions on soil microbial community structures and residues in a tropical forest in Hainan Island, China. *Geoderma* **361**, 114034, doi:https://doi.org/10.1016/j.geoderma.2019.114034 (2020).

5 Huang, Y., Liang, C., Duan, X., Chen, H. & Li, D. Variation of microbial residue contribution to soil organic carbon sequestration following land use change in a subtropical karst region. *Geoderma* **353**, 340-346, doi:https://doi.org/10.1016/j.geoderma.2019.07.028 (2019).

6 Jing, Y. *et al.* Interactive effects of soil warming, throughfall reduction, and root exclusion on soil microbial community and residues in warm-temperate oak forests. *Applied Soil Ecology* **142**, 52-58, doi:https://doi.org/10.1016/j.apsoil.2019.05.020 (2019).

7 Yang, L. *et al.* Conversion of Natural Evergreen Broadleaved Forests Decreases Soil

Organic Carbon but Increases the Relative Contribution of Microbial Residue in Subtropical China. *Forests* **10**, doi:10.3390/f10060468 (2019).

8 Shao, P., Liang, C., Lynch, L., Xie, H. & Bao, X. Reforestation accelerates soil organic carbon accumulation: Evidence from microbial biomarkers. *Soil Biology and Biochemistry* **131**, 182-190, doi:https://doi.org/10.1016/j.soilbio.2019.01.012 (2019).

9 Murugan, R. *et al.* Spatial distribution of microbial biomass and residues across soil aggregate fractions at different elevations in the Central Austrian Alps. *Geoderma* **339**, 1-8, doi:https://doi.org/10.1016/j.geoderma.2018.12.018 (2019).

10 Ma, Z. *et al.* Accumulation of residual soil microbial carbon in Chinese fir plantation soils after nitrogen and phosphorus additions. *Journal of Forestry Research* **29**, 953-962, doi:10.1007/s11676-017-0522-4 (2018).

11 Angst, G. *et al.* Soil organic carbon stocks in topsoil and subsoil controlled by parent material, carbon input in the rhizosphere, and microbial-derived compounds. *Soil Biology and Biochemistry* **122**, 19-30, doi:https://doi.org/10.1016/j.soilbio.2018.03.026 (2018).

12 Sun, H. *et al.* Microbial communities and residues in robinia- and poplar-based alley-cropping systems under organic and integrated management. *Agroforestry Systems* **92**, 35-46, doi:10.1007/s10457-016-0009-x (2018).

13 Shao, S. *et al.* Linkage of microbial residue dynamics with soil organic carbon accumulation during subtropical forest succession. *Soil Biology and Biochemistry* **114**, 114-120, doi:https://doi.org/10.1016/j.soilbio.2017.07.007 (2017).

14 Bai, Z. *et al.* Spatial Heterogeneity of SOM Concentrations Associated with White-rot Versus Brown-rot Wood Decay. *Scientific Reports* **7**, 13758, doi:10.1038/s41598-017-

14181-7 (2017).

15 Ding, X., Zhang, B., Lü, X., Wang, J. & Horwath, W. R. Parent material and conifer biome influence microbial residue accumulation in forest soils. *Soil Biology and Biochemistry* **107**, 1-9, doi:https://doi.org/10.1016/j.soilbio.2016.12.020 (2017).

16 Zhang, W. *et al.* High nitrogen deposition decreases the contribution of fungal residues to soil carbon pools in a tropical forest ecosystem. *Soil Biology and Biochemistry* **97**, 211-214, doi:https://doi.org/10.1016/j.soilbio.2016.03.019 (2016).

17 Khan, K. S., Mack, R., Castillo, X., Kaiser, M. & Joergensen, R. G. Microbial biomass, fungal and bacterial residues, and their relationships to the soil organic matter C/N/P/S ratios. *Geoderma* **271**, 115-123, doi:https://doi.org/10.1016/j.geoderma.2016.02.019 (2016).

18 Siebers, N. *et al.* Origin and Alteration of Organic Matter in Termite Mounds from Different Feeding Guilds of the Amazon Rainforests. *PLOS ONE* **10**, e0123790, doi:10.1371/journal.pone.0123790 (2015).

19 Hatton, P.-J. *et al.* Assimilation and accumulation of C by fungi and bacteria attached to soil density fractions. *Soil Biology and Biochemistry* **79**, 132-139, doi:https://doi.org/10.1016/j.soilbio.2014.09.013 (2014).

20 Freppaz, M. *et al.* Winter–spring transition induces changes in nutrients and microbial biomass in mid-alpine forest soils. *Soil Biology and Biochemistry* **78**, 54-57, doi:https://doi.org/10.1016/j.soilbio.2014.07.010 (2014).

21 Zhang, B., Liang, C., He, H. & Zhang, X. Variations in Soil Microbial Communities and Residues Along an Altitude Gradient on the Northern Slope of Changbai Mountain, China. *PLOS ONE* **8**, e66184, doi:10.1371/journal.pone.0066184 (2013).

22 Klotzbücher, T. *et al.* Lignin properties in topsoils of a beech/oak forest after 8 years of manipulated litter fall: relevance of altered input and oxidation of lignin. *Plant and Soil* **367**, 579-589, doi:10.1007/s11104-012-1489-8 (2013).

23 Pegoraro, R. F., Silva, I. R., Novais, R. F., Barros, N. F. & Fonseca, S. Fenóis derivados da lignina, carboidratos e aminoaçúcares em serapilheira e solos cultivados com eucalipto em sistemas convencional e fertirrigado. *Revista Árvore* **37**, 519-529 (2013).

24 Pegoraro, R. F., Silva, I. R. d., Novais, R. F. d., Barros, N. F. d. & Fonseca, S. Fenóis derivados da lignina, carboidratos e aminoaçúcares em serapilheira e solos cultivados com eucalipto e pastagem. *Revista Árvore* **35**, 359-370 (2011).

25 Moritz, L. K., Liang, C., Wagai, R., Kitayama, K. & Balser, T. C. Vertical distribution and pools of microbial residues in tropical forest soils formed from distinct parent materials. *Biogeochemistry* **92**, 83-94, doi:10.1007/s10533-008-9264-x (2009).

26 Liang, C., Fujinuma, R. & Balser, T. C. Comparing PLFA and amino sugars for microbial analysis in an Upper Michigan old growth forest. *Soil Biology and Biochemistry* **40**, 2063-2065, doi:https://doi.org/10.1016/j.soilbio.2008.01.022 (2008).

27 Van Groenigen, K.-J., Six, J., Harris, D. & Van Kessel, C. Elevated CO2 does not favor a fungal decomposition pathway. *Soil Biology and Biochemistry* **39**, 2168-2172, doi:https://doi.org/10.1016/j.soilbio.2007.03.009 (2007).

28 Jolivet, C., Angers, D. A., Chantigny, M. H., Andreux, F. & Arrouays, D. Carbohydrate dynamics in particle-size fractions of sandy spodosols following forest conversion to maize cropping. *Soil Biology and Biochemistry* **38**, 2834-2842, doi:https://doi.org/10.1016/j.soilbio.2006.04.039 (2006).

29 Turrión, M.-B., Glaser, B. & Zech, W. Effects of deforestation on contents and distribution of amino sugars within particle-size fractions of mountain soils. *Biology and Fertility of Soils* **35**, 49-53, doi:10.1007/s00374-001-0440-6 (2002).

30 ouml, ller, A., Kaiser, K. & Zech, W. Lignin, carbohydrate, and amino sugar distribution and transformation in the tropical highland soils of northern Thailand under cabbage cultivation, <emph type="2">Pinus</emph> reforestation, secondary forest, and primary forest. *Soil Research* **40**, 977-998 (2002).

31 Solomon, D., Fritzsche, F., Tekalign, M., Lehmann, J. & Zech, W. Soil Organic Matter Composition in the Subhumid Ethiopian Highlands as Influenced by Deforestation and Agricultural Management. *Soil Science Society of America Journal* **66**, 68-82, doi:https://doi.org/10.2136/sssaj2002.6800 (2002).

32 Kaiser, K., Guggenberger, G., Haumaier, L. & Zech, W. Seasonal variations in the chemical composition of dissolved organic matter in organic forest floor layer leachates of old-growth Scots pine (Pinus sylvestris L.) and European beech (Fagus sylvatica L.) stands in northeastern Bavaria, Germany. *Biogeochemistry* **55**, 103-143, doi:10.1023/A:1010694032121 (2001).

33 Solomon, D., Lehmann, J. & Zech, W. Land use effects on amino sugar signature of chromic Luvisol in the semi-arid part of northern Tanzania. *Biology and Fertility of Soils* **33**, 33-40, doi:10.1007/s003740000287 (2001).

34 Zhang, X. *et al.* Land-use effects on amino sugars in particle size fractions of an Argiudoll. *Applied Soil Ecology* **11**, 271-275, doi:https://doi.org/10.1016/S0929-1393(98)00136-X (1999).

35 Zhang, X. & Amelung, W. Gas chromatographic determination of muramic acid, glucosamine, mannosamine, and galactosamine in soils. *Soil Biology and Biochemistry* **28**, 1201-1206, doi:https://doi.org/10.1016/0038-0717(96)00117-4 (1996).

36 Wang, Q. Effect of Different Regeneration Methods on Soil Microbial Residue Carbon and Lignin in subtropical Forests. *Fujian Normal University*, (2019).

37 Cui, Y., Zhang, W., He, H., Xie, H., & Zhang, X. Effects of nitrogen addition on transformation of amino sugars in forest soil. *Chinese Journal of Ecology*, **35**, 960-965 (2016). (in Chinese with English abstract).

38 Wang, X., He, H., Hu, G., Shao, P., Zhang, W., Xie, H., & Zhang, X. Effects of substrates on dynamics of amino sugars in two different stages of succession in forest soil. *Journal of Beijing Forestry University*, **38**, 86-93 (2016). (in Chinese with English abstract).

39 Yu, N. Microbial community structure in forest soils at different Dinghu Mountain and its association with carbon accumulation process. *Shenyang Ligong University*, (2013)

40 Li, Y. Effects of warming and nitrogen deposition on soil amino sugar and lignin of Cunninghamia lanceolata in mid-subtropical. *Fujian Normal University*, (2019).

41 Xie, H., Li, W., Bai, Z., He, H., & Zhang, X. Distribution of amino sugars in forest soil profiles of the Changbai Mountain. *Journal of the Graduate School of the Chinese Academy of Sciences*, **25**, 657-664 (2008). (in Chinese with English abstract).

42 Jing, Y., Liu, S., Yin, Y., Deng, J., Liu, Y., Yan, P., & Gou, K. Effects of N-fixing tree species (Alnus sibirica) on amino sugars in the soils of a Larix kaempferi plantation in eastern Liaoning Province, China. *Acta Ecologica Sinica*, **38,** 2838-2845 (2018). (in Chinese with English abstract).

43 Chen, X. *et al.* Land use and mineral fertilization influence soil microbial biomass and residues: A case study of a Chinese Mollisol. *European Journal of Soil Biology* **100**, 103216, doi:https://doi.org/10.1016/j.ejsobi.2020.103216 (2020).

44 Jia, B., Niu, Z., Wu, Y., Kuzyakov, Y. & Li, X. G. Waterlogging increases organic carbon decomposition in grassland soils. *Soil Biology and Biochemistry* **148**, 107927, doi:https://doi.org/10.1016/j.soilbio.2020.107927 (2020).

45 Ding, X. *et al.* Warming yields distinct accumulation patterns of microbial residues in dry and wet alpine grasslands on the Qinghai-Tibetan Plateau. **56**, 881-892 (2020).

46 Luo, R. *et al.* Nutrient addition reduces carbon sequestration in a Tibetan grassland soil: Disentangling microbial and physical controls. *Soil Biology and Biochemistry* **144**, 107764, doi:https://doi.org/10.1016/j.soilbio.2020.107764 (2020).

47 Ding, X., Zhang, B., Wei, Z., He, H. & Filley, T. R. Conversion of grassland into cropland affects microbial residue carbon retention in both surface and subsurface soils of a temperate agroecosystem. *Biology and Fertility of Soils* **56**, 137-143, doi:10.1007/s00374-019-01400-8 (2020).

48 Ding, X. *et al.* Warming increases microbial residue contribution to soil organic carbon in an alpine meadow. *Soil Biology and Biochemistry* **135**, 13-19, doi:https://doi.org/10.1016/j.soilbio.2019.04.004 (2019).

49 Shao, P. *et al.* Responses of microbial residues to simulated climate change in a semiarid grassland. *Science of The Total Environment* **644**, 1286-1291, doi:https://doi.org/10.1016/j.scitotenv.2018.07.055 (2018).

50 Ma, T. *et al.* Divergent accumulation of microbial necromass and plant lignin components

in grassland soils. *Nature Communications* **9**, 3480, doi:10.1038/s41467-018-05891-1 (2018).

51 Guan, Z.-H. *et al.* Conversion of Tibetan grasslands to croplands decreases accumulation of microbially synthesized compounds in soil. **123**, 10-20 (2018).

52 Zhu, X., Liang, C., Masters, M. D., Kantola, I. B. & DeLucia, E. H. The impacts of four potential bioenergy crops on soil carbon dynamics as shown by biomarker analyses and DRIFT spectroscopy. *GCB Bioenergy* **10**, 489-500, doi:https://doi.org/10.1111/gcbb.12520 (2018).

53 Jia, J. *et al.* Comparing microbial carbon sequestration and priming in the subsoil versus topsoil of a Qinghai-Tibetan alpine grassland. *Soil Biology and Biochemistry* **104**, 141-151, doi:https://doi.org/10.1016/j.soilbio.2016.10.018 (2017).

54 Liang, C. *et al.* Microorganisms and their residues under restored perennial grassland communities of varying diversity. *Soil Biology and Biochemistry* **103**, 192-200, doi:https://doi.org/10.1016/j.soilbio.2016.08.002 (2016).

55 Liang, C., Gutknecht, J. & Balser, T. Microbial lipid and amino sugar responses to long-term simulated global environmental changes in a California annual grassland. *Frontiers in Microbiology* **6**, doi:10.3389/fmicb.2015.00385 (2015).

56 Ding, X., Han, X., Zhang, X. & Qiao, Y. Effects of contrasting agricultural management on microbial residues in a Mollisol in China. *Soil and Tillage Research* **130**, 13-17, doi:https://doi.org/10.1016/j.still.2013.02.001 (2013).

57 Liang, C. & Balser, T. C. Warming and nitrogen deposition lessen microbial residue contribution to soil carbon pool. *Nature Communications* **3**, 1222,

doi:10.1038/ncomms2224 (2012).

58 Lauer, F., Kösters, R., du Preez, C. C. & Amelung, W. Microbial residues as indicators of soil restoration in South African secondary pastures. *Soil Biology and Biochemistry* **43**, 787-794, doi:https://doi.org/10.1016/j.soilbio.2010.12.012 (2011).

59 Wichern, J., Wichern, F. & Joergensen, R. G. Impact of salinity on soil microbial communities and the decomposition of maize in acidic soils. *Geoderma* **137**, 100-108, doi:https://doi.org/10.1016/j.geoderma.2006.08.001 (2006).

60 Appuhn, A., Joergensen, R. G., Raubuch, M., Scheller, E. & Wilke, B. The automated determination of glucosamine, galactosamine, muramic acid, and mannosamine in soil and root hydrolysates by HPLC. *Journal of Plant Nutrition and Soil Science* **167**, 17-21, doi:https://doi.org/10.1002/jpln.200321302 (2004).

61 Amelung, W., Kimble, J. M., Samson-Liebig, S. & Follett, R. F. Restoration of Microbial Residues in Soils of the Conservation Reserve Program. *Soil Science Society of America Journal* **65**, 1704-1709, doi:https://doi.org/10.2136/sssaj2001.1704 (2001).

62 Amelung, W., Zhang, X., Flach, K. W. & Zech, W. Amino Sugars in Native Grassland Soils along a Climosequence in North America. *Soil Science Society of America Journal* **63**, 86-92, doi:https://doi.org/10.2136/sssaj1999.03615995006300010014x (1999).

63 Zhou, T., Jiao, K., Qin, S. & Lyu, D. The impact of cover crop shoot decomposition on soil microorganisms in an apple orchard in northeast China. *Saudi Journal of Biological Sciences* **26**, 1936-1942, doi:https://doi.org/10.1016/j.sjbs.2019.07.004 (2019).

64 Zhang, R. Comparision of Nitrogen Utilization by alpine plants and influencn of pasture degradation on Soil and root carbon / carbohydrate in alpine meadow. *Lanzhou*

University, (2015).