Supporting information

Phenological mismatches between above- and below-ground plant responses to climate warming: a global synthesis

Content:

Table S1 Weighted effect size of different phenological parameters among herbaceous and woody plants.

	Estimate (CI)	N	*P*
Herbaceous plants			
Start of above-ground growing season	-2.88 (-1.85~-3.91)	112	<0.001
End of above-ground growing season	-5.06 (-2.85~-7.26)	112	<0.001
Length of above-ground growing season	-2.18 (-0.46~-3.91)	112	<0.05
Start of below-ground growing season	-0.41 (-2.78~1.96)	56	0.74
End of below-ground growing season	-0.66 (-3.46~2.15)	56	0.65
Length of below-ground growing season	-0.25 (-3.60~3.10)	56	0.88
Woody plants			
Start of above-ground growing season	-2.11 (-0.34~-3.88)	70	<0.05
End of above-ground growing season	-1.01 (-3.24~1.22)	70	0.38
Length of above-ground growing season	1.10 (-0.99~3.20)	70	0.30
Start of below-ground growing season	-6.47 (-2.36~-10.58)	34	<0.01
End of below-ground growing season	2.26 (-4.20~8.73)	34	<0.02
Length of below-ground growing season	8.73 (2.20~15.27)	34	<0.01

Table S2 Egger's regression test was used to identify publication bias, $P < 0.05$ suggests the presence of publication bias. If the publication bias exist, Rosenberg fail-safe number was further used to test whether our conclusion was likely to be affected by the nonpublished studies. When the Rosenberg fail-safe number was larger than 5N +10 (N the numbers of the observations), it indicated that the conclusion in our study was not affected by the nonpublished studies.

	P value for Egger's regression test	Rosenberg fail-safe number	5N+10
Herbaceous plants			
Start of above-ground growing season	0.14	-	570
End of above-ground growing season	0.24	-	570
Length of above-ground growing season	0.01	6708	570
Start of below-ground growing season	0.94	-	290
End of below-ground growing season	0.18	-	290
Length of below-ground growing season	0.29	-	290
Woody plants			
Start of above-ground growing season	<0.01	4041	360
End of above-ground growing season	<0.001	19753	360
Length of above-ground growing season	<0.01	41916	360
Start of below-ground growing season	0.80	-	180
End of below-ground growing season	0.69	-	180
Length of below-ground growing season	0.82	-	180

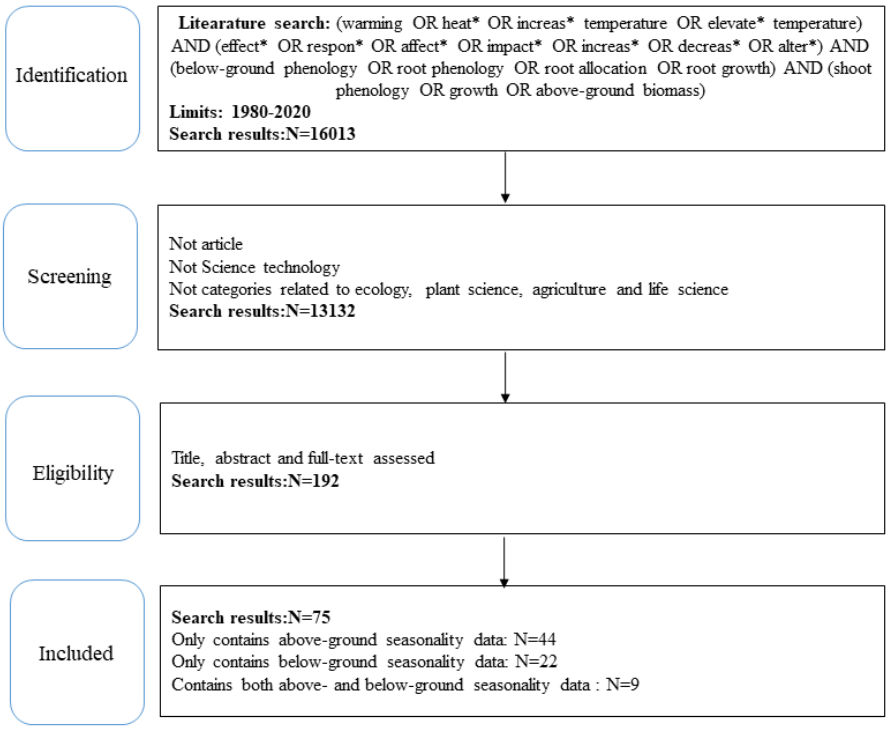
Table S3 Literatures included in the dataset for the meta-analysis.

References	Aboveground phenophases	Belowground phenophases
Adams et al. 2001	Yes	
Arndal et al. 2018		Yes
Bai et al. 2010		Yes
Bannayan et al. 2009	Yes	
Benlloch-González et al. 2016	Yes	
Bronson et al. 2009	Yes	
Carrillo et al. 2014		Yes
Coleman and Bazzaz 1992	Yes	
D'Imperio et al. 2018		Yes
Darrouzet-Nardi et al. 2019		Yes
Edwards et al. 2004		Yes
Esmail and Oelbermann 2011	Yes	
Feng et al. 2017		Yes
Fitter et al. 1999		Yes
Forbes et al. 1997		Yes
Forbes et al. 2020	Yes	
Gavito et al. 2001		Yes
Ge et al. 2012	Yes	Yes
Gruber et al. 2018	Yes	
Hakala and Mela 1996	Yes	
Han et al. 2015	Yes	Yes
Hely and Roxburgh 2005	Yes	
Higuchi et al. 1999	Yes	
Huang et al. 1991		Yes
Hutchison and Henry 2010	Yes	
Johnson et al. 2010		Yes
Kellomäki and Wang 2001	Yes	Yes
King et al. 1999		Yes
Klein et al. 2007	Yes	
Kreyling et al. 2019		Yes
Lahti et al. 2005	Yes	Yes
Lee et al. 2011	Yes	
Lenka et al. 2017	Yes	
Leppälammi-Kujansuu et al. 2014		Yes
Li et al. 2020	Yes	
Lin et al. 2011	Yes	
Mitchell et al. 1993	Yes	
Nissinen et al. 2016	Yes	
Nybakken et al. 2012	Yes	
Oh-e et al. 2007	Yes	

Peltola et al. 2002	Yes	
Pilon et al. 2013		Yes
Pilumwong et al. 2007	Yes	Yes
Radville et al. 2018	Yes	Yes
Randriamanana et al. 2015	Yes	
Reddy et al. 1991	Yes	
Schuerings et al. 2014		Yes
Sheppard and Stanley 2014	Yes	
Shi et al. 2017		Yes
Slaney et al. 2007	Yes	
Sobuj et al. 2018	Yes	
Sønsteby et al. 2012	Yes	
Stenström et al. 2010	Yes	
Stirling et al. 2010	Yes	
Sullivan and Welker 2005	Yes	Yes
Tacarindua et al. 2013	Yes	
Takahashi 2005	Yes	
Tian et al. 211	Yes	
Usami and Lee 2010	Yes	
Veteli et al. 2010	Yes	
Volder et al. 2015	Yes	
Walker et al. 2015	Yes	
Wan et al. 2004		Yes
Wang et al. 2017		Yes
Wang et al. 2010	Yes	
Wang et al. 2016		Yes
Wheeler et al. 2016	Yes	
Wu et al. 2020		Yes
Xiong 2018	Yes	Yes
Xu et al. 2015	Yes	
Xu et al. 2009	Yes	
Yoon et al. 2009	Yes	
Yoshitake et al. 2015	Yes	
Zha et al. 2001	Yes	
Zhang et al. 2020	Yes	

31

Figure S1 Article selection process using Preferred Reporting Items for Systematic Reviews (PRISMA) guidelines.



References

1. **Adams SR, Cockshull KE, Cave CRJ. 2001.** Effect of temperature on the growth and development of tomato fruits. *Annals of Botany* **88**(5): 869-877.
2. **Arndal MF, Tolver A, Larsen KS, Beier C, Schmidt IK. 2018.** Fine root growth and vertical distribution in response to elevated CO_2, warming and drought in a mixed heathland–Grassland. *Ecosystems* 2018(21): 15-30.
3. **Bai W, Wan S, Niu S, Liu W, Chen Q, Wang Q, Zhang W, Han X, Li L. 2010.** Increased temperature and precipitation interact to affect root production, mortality, and turnover in a temperate steppe: implications for ecosystem C cycling. *Global Change Biology* **16**(4): 1306-1316.
4. **Bannayan M, Soler CMT, Garcia AGY, Guerra LC, Hoogenboom G. 2009.** Interactive effects of elevated CO_2 and temperature on growth and development of a short- and long-season peanut cultivar. *Climatic Change* **93**: 389-406.
5. **Benlloch-González M, Quintero JM, Suarez MP, Sánchez-Lucas R, Fernández-Escobar R, Benlloch M. 2016.** Effect of moderate high temperature on the vegetative growth and potassium allocation in olive plants. *Journal of Plant Physiology* **207**: 22-29.
6. **Bronson DR, Gower ST, Tanner M, Van Herk I. 2009.** Effect of ecosystem warming on boreal black spruce bud burst and shoot growth. *Global Change Biology* **15**(6): 1534-1543.
7. **Carrillo Y, Dijkstra FA, Dan LC, Morgan JA, Blumenthal D, Waldron S, Pendall E. 2014.** Disentangling root responses to climate change in a semiarid grassland. *Oecologia* **175**(2): 699.
8. **Coleman JS, Bazzaz FA. 1992.** Effects of CO_2 and temperature on growth and resource use of co-occurring C_3 and C_4 annuals. *Ecology* **73**(4): 1244-1259.
9. **D'Imperio, L., Arndal, M.F., Nielsen, C.S., Elberling, B. & Schmidt, I.K.** (2018) Fast responses of root dynamics to increased snow deposition and summer air temperature in an arctic wetland. *Frontiers in Plant Science*, **9**, 1258.
10. **Darrouzet-Nardi, A., Steltzer, H., Sullivan, P.F., Segal, A., Koltz, A.M., Livensperger, C., Schimel, J.P. & Weintraub, M.N.** (2019) Limited effects of early snowmelt on plants, decomposers, and soil nutrients in Arctic tundra soils. *Ecology & Evolution*, **9**, 1820-1844.
11. **Edwards EJ, Benham DGMarland LA, Fitter AH. 2004.** Root production is determined by radiation flux in a temperate grassland community. *Global Change Biology* **10**(2): 209-227.
12. **Esmail S, Oelbermann M. 2011.** The impact of climate change on the growth of tropical agroforestry tree seedlings. *Agroforestry Systems* **83**(2): 235-244.
13. **Feng J, Xiong D, Deng F, Shi S, Xu S, Zhong B, Chen Y, Chen G. 2017.** Effects of soil warming and precipitation exclusion and their interaction on fine roots production of Chinese fir (*Cunninghamia lanceolata*) seedlings. *Acta Ecologica Sinica* **37**(4) 1119-1126.
14. **Fitter AH, Self GK, Brown TK, Bogie DS, Graves JD, Benham D, Ineson P. 1999.** Root production and turnover in an upland grassland subjected to artificial soil warming respond to radiation flux and nutrients, not temperature. *Oecologia* **120**(4): 575-581.
15. **Forbes PJ, Black KE, Hooker JE. 1997.** Temperature-induced alteration to root longevity in *Lolium perenne*. *Plant & Soil* **190**(1): 87-90.
16. **Forbes, S.J., Cernusak, L.A., Northfield, T.D., Gleadow, R.M., Lambert, S. & Cheesman, A.W.** (2020) Elevated temperature and carbon dioxide alter resource allocation to growth, storage and defence in cassava (Manihot esculenta). *Environmental & Experimental Botany*, 103997.
17. **Gavito ME, Curtis PS, Mikkelsen TN, Jakobsen I. 2001.** Interactive effects of soil temperature,

atmospheric carbon dioxide and soil N on root development, biomass and nutrient uptake of winter wheat during vegetative growth. *Journal of Experimental Botany* **52**(362): 1913-1923.

18. **Ge ZM, Zhou X, Kellomäki S, Peltola H, Biasi C, Shurpali N, Martikainen PJ, Wang KY. 2012.** Measured and modeled biomass growth in relation to photosynthesis acclimation of a bioenergy crop (Reed canary grass) under elevated temperature, CO_2 enrichment and different water regimes. *Biomass & Bioenergy* **46**(46): 251-262.
19. **Gruber A, Oberhuber W, Wieser G. 2018.** Nitrogen addition and understory removal but not soil warming increased radial growth of *Pinus cembra* at treeline in the Central Austrian Alps. *Frontiers in Plant Science* **9**: 1-11.
20. **Hakala, K. & Mela, T.** (1996) The effects of prolonged exposure to elevated temperatures and elevated CO2 levels on the growth, yield and dry matter partitioning of field-sown meadow fescue. *Agricultural &* Food *Science*, **5**, 285-298.
21. **Han S, Lee SJ, Yoon TK, Han SH, Lee J, Kim S, Hwang J, Cho MS, Son YW. 2015.** Species-specific growth and photosynthetic responses of first-year seedlingsof four coniferous species to open-field experimental warming. *Turkish Journal of Agriculture and Forestry* **39**(2): 342-349.
22. **Hely, S.E. & Roxburgh, S.H.** (2005) The interactive effects of elevated CO_2, temperature and initial size on growth and competition between a native C_3 and an invasive C_3 grass. *Plant Ecology*, **177**, 85-98.
23. **Higuchi H, Sakuratani T, Utsunomiya N. 1999.** Photosynthesis, leaf morphology, and shoot growth as affected by temperatures in cherimoya (*Annona cherimola* Mill.) trees. *Scientia Horticulturae* **80**(1): 91-104.
24. **Huang BR, Taylor HM, Mcmichael BL. 1991.** Behavior of lateral roots in winter wheat as affected by temperature. *Environmental & Experimental Botany* **31**(2): 187–192.
25. **Hutchison JS, Henry HAL. 2010.** Additive effects of warming and increased nitrogen deposition in a temperate old field: plant productivity and the importance of winter. *Ecosystems* **13**(5): 661-672.
26. **Johnson MG, Rygiewicz PT, Tingey DT, Phillips DL. 2010.** Elevated CO_2 and elevated temperature have no effect on Douglas-fir fine-root dynamics in nitrogen-poor soil. *New Phytologist* **170**(2): 345-356.
27. **Kellomäki, S. & Wang, K.-Y.** (2001) Growth and resource use of birch seedlings under elevated carbon dioxide and temperature. *Annals of Botany*, **87**, 669-682.
28. **King J, Pregitzer K, Zak D. 1999.** Clonal variation in above- and below-ground growth responses of *Populus tremuloides* Michaux: Influence of soil warming and nutrient availability. *Plant & Soil* **217**(1/2): 119-130.
29. **Klein JA, Harte J, Zhao X-Q. 2007.** Experimental warming, not grazing, decreases rangeland quality on the Tibetan Plateau. *Ecological Applications* **17**(2): 541-557.
30. **Kreyling, J., Grant, K., Hammerl, V., Arfin-Khan, M.A., Malyshev, A.V., Peñuelas, J., Pritsch, K., Sardans, J., Schloter, M. & Schuerings, J.** (2019) Winter warming is ecologically more relevant than summer warming in a cool-temperate grassland. *Scientific Reports*, **9**, 1-9.
31. **Lahti M, Aphalo PJ, Finer L, Ryyppo A, Lehto T, Mannerkoski H. 2005.** Effects of soil temperature on shoot and root growth and nutrient uptake of 5-year-old Norway spruce seedlings. *Tree Physiology* **25**(1): 115-122.
32. **Lee JS. 2011.** Combined effect of elevated CO_2 and temperature on the growth and phenology of two annual C_3 and C_4 weedy species. *Agriculture Ecosystems & Environment* **140**(3): 484-491.

33. **Lenka, N.K., Lenka, S., Thakur, J., Elanchezhian, R., Aher, S., Simaiya, V., Yashona, D., Biswas, A., Agrawal, P. & Patra, A.** (2017) Interactive effect of elevated carbon dioxide and elevated temperature on growth and yield of soybean. *Current Science*, **113**, 2305.
34. **Leppälammi-Kujansuu, J., Salemaa, M., Kleja, D.B., Linder, S. & Helmisaari, H.-S.** (2014) Fine root turnover and litter production of Norway spruce in a long-term temperature and nutrient manipulation experiment. *Plant & Soil*, **374**, 73-88.
35. **Li, Y., Hou, R. & Tao, F.** (2020) Interactive effects of different warming levels and tillage managements on winter wheat growth, physiological processes, grain yield and quality in the North China Plain. *Agriculture, Ecosystems & Environment*, **295**, 106923.
36. **Lin X, Zhang Z, Wang S, Hu Y, Xu G, Luo C, Chang X, Duan J, Lin Q, Xu B. 2011.** Response of ecosystem respiration to warming and grazing during the growing seasons in the alpine meadow on the Tibetan plateau. *Agricultural & Forest Meteorology* **151**(7): 792-802.
37. **Mitchell Rac, Mitchell Vj, Driscoll Sp, Franklin J, Lawlor Dw. 1993.** Effects of increased CO_2 concentration and temperature on growth and yield of winter wheat at two levels of nitrogen application. *Plant, Cell & Environment* **16**(5): 521-529.
38. **Nissinen K, Nybakken L, Virjamo V, Julkunentiitto R. 2016.** Slow-growing Salix repens (*Salicaceae*) benefits from changing climate. *Environmental and Experimental Botany* **128**: 59-68.
39. **Nybakken L, Hörkkä R, Julkunen-Tiitto R. 2012.** Combined enhancements of temperature and UVB influence growth and phenolics in clones of the sexually dimorphic *Salix myrsinifolia*. *Physiologia Plantarum* **145**(4): 551-564.
40. **Oh-e I, Saitoh K, Kuroda T. 2007.** Effects of high temperature on growth, yield and dry-matter production of rice grown in the paddy field. *Plant Production Science* **10**(4): 412-422.
41. **Peltola H, Kilpeläinen A, Kellomäki S. 2002.** Diameter growth of Scots pine (*Pinus sylvestris*) trees grown at elevated temperature and carbon dioxide concentration under boreal conditions. *Tree Physiology* **22**(14): 963-972.
42. **Pilon R, Picon-Cochard C, Bloor JMG, Revaillot S, Kuhn E, Falcimagne R, Balandier P, Soussana J-F. 2013.** Grassland root demography responses to multiple climate change drivers depend on root morphology. *Plant and Soil* **364**(1): 395-408.
43. **Pilumwong J, Senthong C, Srichuwong S, Ingram KT. 2007.** Effects of temperature and elevated CO_2 on shoot and root growth of peanut (*Arachis hypogaea L.*) grown in controlled environment chambers. *Scienceasia* **33**(1): 79-87.
44. **Radville L, Post E, Eissenstat DM. 2018.** On the sensitivity of root and leaf phenology to warming in the Arctic. *Arctic Antarctic & Alpine Research* **50**(1): S100020.
45. **Randriamanana, T.R., Lavola, A. & Julkunen-Tiitto, R.** (2015) Interactive effects of supplemental UV-B and temperature in European aspen seedlings: Implications for growth, leaf traits, phenolic defense and associated organisms. *Plant Physiology & Biochemistry*, **93**, 84-93.
46. **Reddy KR, Hodges HF, Mckinion JM, Wall GW. 1991.** Temperature effects on pima cotton growth and development. *Agronomy Journal* **84**(2): 237-243.
47. **Schuerings J, Jentsch A, Walter J, Kreyling J. 2014.** Winter warming pulses differently affect plant performance in temperate heathland and grassland communities. *Ecological Research* **29**(4): 561-570.
48. **Sheppard CS, Stanley MC. 2014.** Does elevated temperature and doubled CO_2 increase growth of three potentially invasive plants? *Invasive Plant Science & Management* **7**(2): 237-246.
49. **Shi SZ, Xiong DC, Deng F, Feng JX, Chen-Sen XU, Zhong BY, Chen YY, Chen GS, Yang YS.**

2017. Interactive effects of soil warming and nitrogen addition on fine root production of Chinese fir seedlings. *Chinese Journal of Plant Ecology* **41**(2): 186-195.

50. **Slaney, M., Wallin, G., Medhurst, J. & Linder, S.** (2007) Impact of elevated carbon dioxide concentration and temperature on bud burst and shoot growth of boreal Norway spruce. *Tree Physiology*, **27**, 301-312.
51. **Sobuj N, Virjamo V, Zhang Y, Nybakken L, Julkunentiitto R. 2018.** Impacts of elevated temperature and CO_2 concentration on growth and phenolics in the sexually dimorphic *Populus tremula* (L.). *Environmental and Experimental Botany* **146**: 34-44.
52. **Sønsteby A, Heide OM. 2012.** Effects of photoperiod and temperature on growth, flowering and fruit yield in annual-fruiting red raspberry cultivars (*Rubus idaeus L.*). *European Journal of Horticultural Science* **77**(3): 97-108.
53. **Stenström A, Jónsdóttir IS. 2010.** Responses of the clonal sedge, Carex bigelowii, to two seasons of simulated climate change. *Global Change Biology* **3**(S1): 89-96.
54. **Stirling CCM, Jones ML, Ashenden TW, Sparks TH. 2010.** Effects of elevated CO_2 and temperature on growth and allometry of five native fast-growing annual species. *New Phytologist* **140**(2): 343-354.
55. **Sullivan, P.F. & Welker, J.M.** (2005) Warming chambers stimulate early season growth of an arctic sedge: results of a minirhizotron field study. *Oecologia*, **142**, 616-626.
56. **Tacarindua CRP, Shiraiwa T, Homma K, Kumagai E, Sameshima R. 2013.** The effects of increased temperature on crop growth and yield of soybean grown in a temperature gradient chamber. *Field Crops Research* **154**(3): 74-81.
57. **Takahashi K. 2005.** Effects of artificial warming on shoot elongation of alpine dwarf pine (*pinus pumila*) on mount shogigashira, central Japan. *Arctic Antarctic & Alpine Research* **37**(4): 620-625.
58. **Usami T, Lee JT. 2010.** Interactive effects of increased temperature and CO_2 on the growth of Quercus *myrsinaefolia* saplings. *Plant Cell & Environment* **24**(10): 1007-1019.
59. **Veteli TKK, Julkunen-Tiitto R, Roininen H, Tahvanainen J. 2010.** Effects of elevated CO_2 and temperature on plant growth and herbivore defensive chemistry. *Global Change Biology* **8**(12): 1240-1252.
60. **Volder A, Gifford RM, Evans JR. 2015.** Effects of elevated atmospheric CO_2 concentrations, clipping regimen and differential day/night atmospheric warming on tissue nitrogen concentrations of a perennial pasture grass. *Global Change Biology* **7**: plv094.
61. **Walker, T.N., Ward, S.E., Ostle, N.J. & Bardgett, R.D.** (2015) Contrasting growth responses of dominant peatland plants to warming and vegetation composition. *Oecologia*, **178**, 141-151.
62. **Wan SQ, Norby RJPregitzer KS, Ledford J, O'Neill EG. 2004.** CO_2 enrichment and warming of the atmosphere enhance both productivity and mortality of maple tree fine roots. *New Phytologist* **162**(2): 437-446.
63. **Wang, C., Zhao, X., Zi, H., Hu, L., Ade, L., Wang, G. & Lerdau, M.** (2017) The effect of simulated warming on root dynamics and soil microbial community in an alpine meadow of the Qinghai-Tibet Plateau. *Applied Soil Ecology*, **116**, 30-41.
64. **Wang, J.-F., Gao, S., Lin, J.-X., Mu, Y.-G. & Mu, C.-S.** (2010) Summer warming effects on biomass production and clonal growth of Leymus chinensis. *Crop & Pasture Science*, **61**, 670-676.
65. **Wang, Z., Ding, L., Wang, J., Zuo, X., Yao, S. & Feng, J.** (2016) Effects of root diameter, branch order, root depth, season and warming on root longevity in an alpine meadow. *Ecological Research*, **31**, 739-747.

66. **Wheeler JA, Gonzalez NM, Stinson KA. 2016.** Red hot maples: Acer rubrum first-year phenology and growth responses. *Canadian Journal of Forest Research* **47**(2): 159-165.
67. **Wu, Y., Zhu, B., Eissenstat, D.M., Wang, S., Tang, Y. & Cui, X**. (2020) Warming and grazing interact to affect root dynamics in an alpine meadow. *Plant & Soil*, 1-16.
68. **Xiong D. 2018.** Interactive effects of warming and nitrogen addition on fine root dynamics of a young subtropical plantation. *Soil Biology and Biochemistry* **123**: 180-189.
69. **Xu MH, Peng F, You QG, Guo J, Tian XF, Liu M, Xue X. 2015.** Effects of warming and clipping on plant and soil properties of an alpine meadow in the Qinghai-Tibetan Plateau, China. *Journal of Arid Land* **7**(2): 189-204.
70. **Xu, Z., Hu, T., Zhang, L., Zhang, Y., Xian, J. & Wang, K.** (2009) Effects of simulated warming on the growth, leaf phenology, and leaf traits of Salix eriostachya in sub-alpine timberline ecotone of western Sichuan, China. *The Journal of Applied Ecology*, **20**, 7-12.
71. **Yoon STH, Gerrit, Flitcroft I, Bannayan M. 2009.** Growth and development of cotton (Gossypium hirsutum L.) in response to CO_2 enrichment under two different temperature regimes. *Environmental & Experimental Botany* **67**(1): 178-187.
72. **Yoshitake S, Tabei N, Mizuno Y, Yoshida H, Sekine Y, Tatsumura M, Koizumi H. 2015.** Soil microbial response to experimental warming in cool temperate semi-natural grassland in Japan. *Ecological Research* **30**(2): 235-245.
73. **Tian, Y., Jin, C., Ai-Xing, D., Jian-Chu, Z. & Wei-Jian, Z.** (2011) Effects of asymmetric warming on the growth characteristics and yield components of winter wheat under free air temperature increased. *The Journal of Applied Ecology*, **22**, 681-686.
74. **Zha T, ., Ryyppö A, ., Wang KY, KellomäKi S, . 2001.** Effects of elevated carbon dioxide concentration and temperature on needle growth, respiration and carbohydrate status in field-grown Scots pines during the needle expansion period. *Tree Physiology* **21**(17): 1279-1287.
75. **Zhang, L., Zhong, B., Chen, T., Xiong, D., Yan, X. & Chen, G.** (2020) Effects of air and soil warming on aboveground phenology and growth of Cunninghamia lanceolata seedlings. *Acta Ecologica Sinica*. 40, 4146-4156.