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气温、CO_2浓度和降水交互作用对作物生长和产量的影响

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摘 要 气温、大气 CO_2 浓度和降水等气候因子是影响作物生长发育的关键因子,而不同的气候因子对作物的影响并非独立的,多气候因子交互作用对作物的影响目前已成为研究的焦点问题.研究不同气候因子交互作用的影响,其结果更接近作物生长的实际情况,有助于了解作物甚至作物生态系统对气候变化的真实响应.国内外关于不同气候因子对作物影响的报道较多,要全面总结不同气候因子交互作用对作物的影响是非常困难的.因此,本文只对近年来有关气温升高、大气 CO_2 浓度增加和降水变化交互作用对作物生长发育、光合生理及产量影响的研究进展做一简要评述,并提出目前研究的不足和需要解决的关键问题,以期为气候变化对作物生长发育及产量影响的研究提供参考.

关键词 交互作用; 气温升高; CO_2 浓度升高; 降水变化; 作物

Interactive effects of temperature, CO_2 concentration and precipitation on growth and yield of crops. MENG Fan-chao[1], GUO Jun[1*], ZHOU Li[2], XIONG Ming-ming[1], ZHANG Lei[3] ([1]*Tianjin Climate Center*, *Tianjin* 300074, *China*; [2]*Institute of Eco-environment and Agro-meteorology*, *Chinese Academy of Meteorological Sciences*, *Beijing* 100081, *China*; [3]*National Meteorological Information Center*, *China Meteorological Administration*, *Beijing* 100081, *China*).

Abstract: Temperature, CO_2 concentration and precipitation are the key climate factors affecting crop growth and yield. The effects of different climate factors on crops are not independent, and their interactive effects on crops have become a focus in this research field. The study of interactive effects of multiple climate factors on crops could more reliably reflect the actual situations of crop growth, which could help us to understand the crop growth and even the ecosystem response to climate change, and optimize agricultural production managements in the future. In recent years, there are a lot of reports about the effects of different climate factors on crops both in China and abroad, and thus it is quite difficult to conduct a comprehensive review for interactive effects of all climatic factors on crops. Therefore, this review only focused on the results of the interactive effects of warming, elevated CO_2 concentration and changing precipitation on crop growth, photosynthetic physiology, and yield in recent years, and identified the knowledge gaps of the relevant studies and the key issues that urgently need to be solved in future research. This would be useful for the researches elucidating the influence of climate change on crop growth and yield.

Key words: interactive effects; warming; elevated CO_2 concentration; changing precipitation; crops.

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全球气候变化的基本特征包括气温升高、大气 CO_2 浓度升高和降水格局变化等[1].据 IPCC[1] 报道,1880—2012 年,全球平均地表气温升高了约 0.85 ℃,过去的 3 个连续 10 年比自 1850 年以来的任何一个 10 年都暖.IPCC 第五次评估报告中,采用新排放情景和 CMIP5 进行的模拟结果表明,与 1986—2005 年相比,预计 2016—2035 年和 2081—2100 年全球平均地表气温将升高 0.3~0.7 ℃和 0.3~4.8 ℃[1].同时,大气中 CO_2 浓度持续上升,比工业化前高出约 41%[1],预估到 2050 年将达到 550 $\mu mol \cdot mol^{-1}$[2].另外,气候变暖和温室效应的产生将影响水分平衡,使全球和次大陆尺度季节性降水格局发生变化[3-6],不同地区的水资源减少或增加,变幅在 10%左右[7].

大量研究表明,气候变化对农作物生长及产量存在重要影响[8-9].气温升高、大气 CO_2 浓度升高和降水变化作为全球气候变化的主要表现,将直接或者间接影响植物的光合作用和 C 代谢过程[10-12].但是,关于气候因子对作物影响的研究很多针对气温、CO_2 浓度和降水等单因子水平,而在实际情况下,各气候因子往往同时发生变化而具有交互作用,单因子试验很难反映自然状况.气温、CO_2 浓度和降水等气候因子对作物的影响并非是独立的,多因子间的交互作用对农作物的生长发育和生理生态机制的影响越来越受到研究者的重视[13-16].本文从气温、CO_2 浓度和降水等气候因子交互作用对作物的生长发育、光合生理及产量等几方面梳理已有国内外文献,对当前不同气候因子交互作用对作物影响存在的争论及生理机制进行了综述,分析了目前研究的不足,以期为本领域相关研究提供参考.

1 气温升高与降水变化交互作用对作物的影响

1.1 气温升高与降水变化交互作用对作物生长发育的影响

气温和降水都是影响作物生长发育的重要气候因子.观测发现,增温和降水变化的交互作用对拔节期春小麦株高无显著影响[17],而在小麦成熟后,高温和干旱交互作用会使小麦(*Triticum aestivum*)的分蘖数明显减少[18].作物对高温和干旱胁迫的响应程度因部位不同而不同,如玉米根系受干旱的影响更大,而叶片受高温的影响更大[19].作物对增温和降水的响应在白天和夜间也有所不同,自然降水条件下,夜间增温时,会使玉米叶片的呼吸作用增强,消耗更多的有机物,进而使干物质积累量减少[20-22].增温和降水减少的交互作用对春小麦地上部干物质积累的负面效应显著,而增加降水在一定程度上可以缓解这种影响[17].刘瑞侠等[19]研究还表明,供试玉米幼苗的叶与根的酶活性在干旱和高温交互作用下较干旱或高温单因子处理明显升高,证明了干旱与高温交互作用对幼苗的危害更大.但经历过高温或者干旱锻炼的作物会对二因子的交互作用产生一定的抵抗力和适应性.如王鹤龄等[23]研究高温和干旱胁迫交互作用对春小麦不同生育时期的影响时发现,春小麦在经历过拔节期的干旱后,其在灌浆期忍耐干旱和高温事件的能力提高.

1.2 气温升高与降水变化交互作用对作物光合生理的影响

气温升高与降水变化交互作用对作物光合参数影响较大.研究发现,在增加降水和水分不变条件下,1 ℃增温有利于拔节期春小麦叶片净光合速率(P_n)的提高,而 2~3 ℃增温则限制了其光合作用,即暖干化不利于小麦拔节期光合作用的进行;在降水减少条件下,增温显著阻碍了春小麦后期光合作用的进行,而增加降水量对增温条件下的光合具有一定的补偿作用[17].高温和干旱胁迫都可以降低作物的 P_n, Dekov 等[24] 通过试验发现,玉米(*Zea mays*)的 P_n 在高温、干旱和二者交互作用下显著下降,而向日葵(*Helianthus annuus*)对二者交互作用更为敏感.

研究表明,P_n 的下降可能与气孔变化有关,对高温和干旱环境中作物的气孔反应的研究结果较为一致,即叶片的气孔部分关闭和气孔导度(g_s)下降,导致叶片的 P_n 及蒸腾速率(T_r)等明显降低[17,25-26].孟凡超等[27]研究认为,在水分不足的条件下,增温显著降低了玉米叶片的 T_r,增加降水可以在一定程度上缓解增温对玉米叶片呼吸作用的负效应.对水分利用效率(WUE)的影响上,王鹤龄等[17]研究表明,增温后,春小麦拔节期的 WUE 降低,并以降水减少处理下降最为明显,但是在降水增加和降水不变的处理上表现不显著.这些表现与气温升高和降水减少共同作用加快了田间蒸散和作物蒸腾作用,引起水分的大量散失有关.对干旱、高温和二者交互作用对玉米叶片相对水分含量影响的研究认为,与对照相比,干旱条件下叶片相对含水量降低 10.9%,在高温条件下降低 7%,二者交互作用下降低32.7%[24].对我国南方红壤区高温和土壤水分胁迫交互作用的研究表明,高温加剧了水分胁迫,二者交互作用将导致季节性干旱胁迫[28].总体来说,与单个因子作用

相比,高温和干旱的综合作用导致各气体交换指标大幅度降低[18].

1.3　气温升高与降水变化交互作用对作物产量的影响

Hassan[25]用气室研究了小麦对干旱、气温升高的响应,结果发现,在干旱条件下小麦籽粒产量下降21%,气温升高条件下增加了 26%.Schlenker 等[29]对 5 种作物研究得出,撒哈拉沙漠以南地区气温对作物产量的影响(−38%~12%)较降水(−3%~3%)更显著.Jones 等[30]预测到 2055 年,在气温变暖、降水减少的背景下,玉米产量会有约 10%的减产.王伟东等[31]发现,在玉米灌浆期发生高温和干旱胁迫会造成粒重大幅度降低,高粱籽粒产量也随着高温和干旱胁迫的时间和程度而减少[32].在我国小麦产区,高温与干旱经常同时发生形成干热风,如小麦灌浆期遇干热风,植株体内水分平衡将被扰乱,绿叶面积迅速减少,阻碍光合同化产物向籽粒的运输,缩短灌浆期,使籽粒充实度变差[33].反之,降水过多不利于玉米生产,而在水分供应充足的条件下,增温会增加干物质的积累[34].

气温升高和降水变化交互作用对作物的影响因不同的增温和降水幅度而有所差异.王鹤龄等[23]在甘肃定西地区开展了红外增温模拟试验,对气温升高和降水变化对春小麦产量影响的研究结果表明,增温幅度小于 2 ℃时,降水变化对春小麦穗粒数影响不显著;当增温为 3 ℃时,降水减少显著减低穗粒数,降水增加显著增加穗粒数.随气温的增加,春小麦不孕小穗率呈二次曲线上升,其中降水减少叠加增温 3℃可使不孕小穗率达到 45%[17].在降水充沛、水分条件比较适宜的地区,气温升高对高纬度地区的玉米生产是有利的,如气候变暖有利于东北地区玉米单产的提高[35],因为春夏季气温升高,使玉米生长季延长,有利于玉米生长发育和干物质积累;但对于那些高温但降水较少、水分亏缺的地区,增温会造成玉米产量的下降或不稳定[22].

2　CO_2 浓度升高与降水变化交互作用对作物的影响

2.1　CO_2 浓度升高与降水变化交互作用对作物生长发育的影响

CO_2 浓度升高对作物的生长发育和生理生化等过程起到正向促进作用[13,36-37],CO_2 浓度升高在不同水分条件下对作物生长发育的影响不同,在干旱条件下的促进作用较湿润条件下明显[37-41].在叶面积上,研究认为,高浓度 CO_2 使农作物叶面积显著增加,干旱条件下的增幅明显大于湿润条件下[38].玉米在 CO_2 浓度升高和降水增加交互作用下,叶面积也有不同程度的增加,以 550 μmol · mol^{-1} 和降水增加 15%交互作用为最大[27].而对生物量的影响研究结果不同:在水分充足的条件下,CO_2 浓度升高对玉米和高粱的生物量积累没有显著的影响[42],甚至有研究认为是负效应[43];而 Cure 等[44]对气室研究的综述表明,当 CO_2 浓度升高(约 550 μmol · mol^{-1})时,玉米和高粱等 C4 植物在湿润和干旱条件下的生物量分别增加 7%和 19%.同样,在牧草方面的研究也表明,高 CO_2 浓度(550 μmol · mol^{-1})和降水增加 15%可以促进短花针茅(*Stipa breviflora*)总叶面积达到最大、叶片数增加和总生物量的提高[45].

2.2　CO_2 浓度升高与降水变化交互作用对作物光合生理的影响

国内外关于 CO_2 浓度升高和水分变化交互作用对不同作物光合作用影响的研究均发现,干旱条件下 CO_2 浓度升高较湿润条件下对作物光合速率的促进作用明显.CO_2 浓度升高条件下,干旱处理的春小麦叶片光合速率增幅大于湿润处理[46-47];Wall 等[48]应用自由大气 CO_2 浓度升高(FACE)系统对高粱的观测发现,CO_2 浓度升高使两季高粱在不同生育期中午时的 P_n 平均值增加 15%,其中,在干旱条件下增加 23%,在湿润条件下增加 9%;在大麦(*Hordeum vulgare*)上的研究认为,CO_2 浓度升高使叶片净同化速率在干旱条件下增加 37%,在湿润条件下增加 23%[49].

在二因子交互作用对作物叶片蒸腾速率和气孔的影响方面(图 1),Woodwell[50]首次证实了植物的气孔密度与大气 CO_2 浓度呈负相关关系.Murray[51]和 Ainsworth 等[52]认为,CO_2 浓度增加引起 g_s 降低和气孔的部分关闭; Curtis 等[53]通过观测试验得出 CO_2 倍增使 g_s 平均减小 11%;高浓度 CO_2 下两季高粱不同生育时期中午的 g_s 平均下降 35%,其中,干旱条件下下降了 32%,而在湿润条件下下降了 37%[48];Cure[54]认为,在水分和 N 充足条件下,CO_2 浓度升高到 550 μmol · mol^{-1} 可使高粱和玉米叶片 g_s 平均减少 21%和 15%.g_s 下降的同时,叶片 T_r 随之下降,550 μmol · mol^{-1} CO_2 浓度可使高粱和玉米叶片平均 T_r 减少 15%[44],且一般在湿润条件下较干旱条件下降幅增大[38].在 CO_2 浓度升高和降水增加

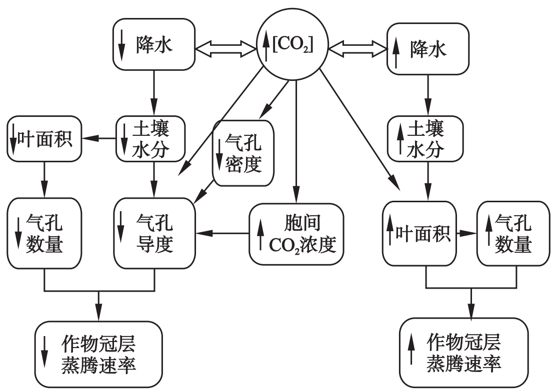

图 1 CO_2 浓度升高和降水变化交互作用下作物蒸腾速率变化的可能机理

Fig.1 Possible mechanism of crop transpiration rate change under interactive effects of elevated CO_2 concentration and changing precipitation.

条件下的试验表明,玉米叶片 T_r 随水分增加而升高[55].研究认为,T_r 的下降与 g_s 降低有关,叶片 g_s 随 CO_2 浓度升高而下降,增大了水分由作物叶片向外排放的阻力,从而使 T_r 下降[56].另外,王润佳等[57]认为,g_s 的下降与胞间 CO_2 浓度(C_i)升高有关,随着 CO_2 浓度升高 C_i 不断增加,作物通过调节气孔开闭程度来降低 C_i,以保持胞间 CO_2 分压始终低于大气 CO_2 分压.总之,高 CO_2 浓度和干旱交互作用导致的气孔密度和 g_s 下降减少了作物水分的蒸腾损失,使土壤水分下降速率减慢,可以间接地促进干旱环境下作物的光合作用,提高水分利用效率[58-59],缓解水分胁迫的影响,增强作物的抗干旱能力.

2.3 CO_2 浓度升高与降水变化交互作用对作物产量的影响

CO_2 浓度升高的"气肥"作用促进作物产量的提高.气室观测数据显示,CO_2 倍增使玉米平均增产 27%($n=3$)[44].550 μmol · mol^{-1} CO_2 浓度使 C4 作物(高粱和玉米)籽粒产量平均增加 18% ($n=14$,其中玉米 9 个,高粱 5 个)[13].CO_2 浓度升高与降水变化交互作用对作物产量的影响比较复杂.在水分亏缺条件下,CO_2 浓度升高对玉米和高粱的产量具有促进作用[60-61].Leakey 等[62]指出,对于 C4 植物来说,CO_2 浓度升高主要是通过改变其水分状况而使其增产,解释了玉米和高粱等 C4 植物在水分亏缺条件下施肥效应明显的原因.但是在湿润条件下,CO_2 浓度升高对作物产量影响的报道不一.Amthor 等[63]和 Reeves[64]认为,CO_2 浓度升高和水分增加显著增加了作物产量;Meng 等[65]研究也发现,东北玉米对 CO_2 浓度升高和降水增加的交互作用显著促进了果穗的孕育,使果穗体积增大,玉米籽粒产量增加,增加幅度因不同 CO_2 浓度和降水增加量而不同.有研究认为,二因子交互作用对作物没有显著影响[42].Ellis 等[43]认为,二因子交互作用对作物的影响呈负效应.Maricopa 的 FACE 试验也表明,在高浓度 CO_2 和湿润条件下,高粱产量较对照降低 4%,但由于数据变异很大,未达到显著水平[61].

3 气温与 CO_2 浓度升高交互作用对作物的影响

3.1 气温与 CO_2 浓度升高交互作用对作物生长发育的影响

气温影响 CO_2 的"施肥效应",二者交互作用对作物形态结构的影响因不同气温、不同作物及不同发育期而不同.郭建平等[66]应用人工气候室试验发现,在相同的发育期,高温和高 CO_2 浓度使作物叶面积、根、茎、叶生长量不足,生物量下降,表明当气温升高到一定程度后,高温对作物的负效应已超过 CO_2 浓度带来的正效应,从而对作物的生长发育不利.苏营等[67]对大豆(*Glycine max*)的观测也表明,CO_2 浓度升高对大豆株高和茎粗的生长具有促进作用,增温使这种促进作用更大.Kim 等[68]设置了当前 CO_2 浓度(370 μmol · mol^{-1})和 CO_2 浓度倍增条件(750 μmol · mol^{-1}),研究增温对玉米的影响,结果发现,无论在当前 CO_2 浓度还是 CO_2 浓度倍增条件下,增温对玉米叶片伸长速率、叶面积的影响无明显差别.赖上坤等[69]应用稻田 FACE 系统研究 CO_2 浓度升高(较对照增加 200 μmol · mol^{-1})和气温升高(较对照增加 2 ℃)对超级杂交籼稻生长发育的影响发现,与对照相比,同时升高 CO_2 浓度和气温可使成熟期叶片、茎鞘、稻穗及地上部干质量分别增加 40%、47%、10%和 18%,但增幅略小于单独 CO_2 浓度升高处理.

3.2 气温与 CO_2 浓度升高交互作用对作物光合生理的影响

CO_2 浓度升高对作物光合作用的影响往往与气温变化有关.研究表明,CO_2 浓度升高使小麦叶片 CO_2 光合同化速率提高的正效应随气温的升高而增加[70-71].在不同气温范围内,作物对 CO_2 浓度升高的响应不同.在达到最适气温之前,气温与 CO_2 浓度升高交互作用对作物光合作用具有协同促进效应[14,58,72].在超过最适气温以后,高温并没有提高 CO_2 浓度升高对光合作用的促进作用[73].各季节气温不同,导致 CO_2 浓度升高对作物光合作用的影响

随季节不同而有所差异，高 CO_2 浓度对作物光合作用的促进作用在夏季高于冬季[72]. 同时，随 CO_2 浓度升高，作物进行光合作用的最适气温也会升高 5~10 ℃[70]. 但是，二因子交互作用在作物群体上的表现较为不明显. Clifford 等[74] 研究认为，花生(*Arachis hypogaea*)植株单叶光合作用受气温与 CO_2 浓度升高交互的促进作用大于群体. 甚至气温和 CO_2 浓度对作物群体光合的促进作用会随时间的推移而减弱[75].

在气温和 CO_2 浓度升高对作物蒸腾作用的影响方面，Markelz 等[39] 发现，在相同气温条件下，CO_2 浓度升高会降低作物蒸腾作用强度，提高作物水分利用效率. Zhou 等[72] 认为，CO_2 浓度升高抑制作物的蒸腾作用，使作物全生育期的蒸发蒸腾量减少. Wallace[7] 和 Leakey 等[37] 也认为，CO_2 浓度升高可以增加叶片气孔阻抗，减少水分散失，使叶片蒸腾降低. 但是，有研究持相反观点. de Souza 等[76] 发现，CO_2 浓度升高引起气温升高，将增加作物的蒸腾作用. 另外，Burkart 等[77] 研究发现，CO_2 浓度升高增加了小麦群体的叶面积指数，这将抵消一部分因气孔阻力变大而引起的蒸腾减少的效应. Prior 等[78] 认为，CO_2 浓度升高引起的蒸散量的减少可由气温升高和叶面积指数增加带来的蒸散量的增加来补偿，有时甚至过补偿(图 2). 在气温和 CO_2 浓度升高对作物暗呼吸速率的影响方面，在气温和 CO_2 浓度交互作用对冬小麦影响的试验中发现，CO_2 浓度升高抑制冬小麦叶片暗呼吸作用，暗呼吸速率随 CO_2 浓度升高而呈线性下降趋势，而气温和 CO_2 浓度对冬小麦叶片暗呼吸速率的影响是相互独立的[79].

3.3 气温与 CO_2 浓度升高交互作用对作物产量的影响

在气温和 CO_2 浓度升高对稻田的影响上，Kim 等[80] 和 Nam 等[81] 研究发现，同时增温和增加 CO_2 浓度条件下，水稻生物量增长明显. 周超等[82] 研究认为，气温升高对水稻产量的影响不显著，而 CO_2 浓度升高导致水稻产量显著增加. 研究表明，水稻产量随 CO_2 浓度升高而升高，随温度升高，水稻仍然对 CO_2 浓度的提高有积极的响应[83]；低温和 CO_2 浓度升高交互作用下大豆的地上部生物量也显著提高[84]. Wheeler 等[85] 也发现，CO_2 浓度升高使小麦粒重、籽粒成熟率和籽粒饱满度增加，但高温却抵消了这些贡献. Lal 等[86] 应用 CERES 模型模拟得出，CO_2 浓度倍增可使小麦和水稻分别增产 28% 和 15%，但是分别升温 3 和 2 ℃ 足以将这种增产作用抵消. 李广等[87] 应用 APSIM 模型模拟研究也认为，增温对旱地春小麦产量影响的负效应大于高 CO_2 浓度带来的正效应. Ruiz-Vera 等[88] 应用 FACE 和红外增温系统使 CO_2 浓度升高 200 $\mu mol \cdot mol^{-1}$，并使玉米冠层增温 3.5 ℃，研究玉米全生育期生物量及籽粒产量对增温和 CO_2 浓度升高的响应，结果发现，冠层升温和 CO_2 浓度升高交互作用使玉米产量降低，经济系数下降.

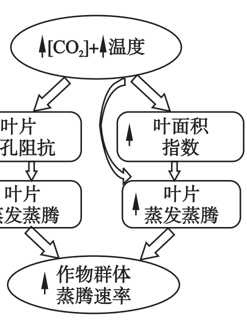

图 2　气温和 CO_2 浓度升高的交互作用下作物蒸腾速率变化的可能机理

Fig.2　Possible mechanism of crop transpiration rate change under interactive effects of warming and elevated CO_2 concentration.

4　气温、CO_2 浓度升高与降水变化交互作用对作物的影响

Yang 等[89] 模拟了 CO_2 浓度升高、气温和降水变化对华北平原冬小麦产量的影响，指出当 CO_2 浓度升高到 680 $\mu mol \cdot mol^{-1}$ 时，三因子的共同作用将使冬小麦平均产量在灌溉和雨养处理下分别增加 23.1% 和 27.7%. 廖建雄等[90] 应用开顶式气室在气温升高(高于正常日平均气温约 4.8 ℃)和 CO_2 浓度升高(550 和 700 $\mu mol \cdot mol^{-1}$)条件下，对春小麦设置高、中、低 3 个水分梯度(田间持水量的 75%~85%、55%~65% 和 35%~45%)试验，结果表明，三因子交互作用使小麦光合速率、叶片和群体水平的水分利用效率增大，气孔阻力明显增加；对蒸发蒸腾的影响较为复杂，在高、中水分条件下，气温和 CO_2 浓度升高使蒸发蒸腾量增加，而在低水分条件下，气温和 CO_2 浓度升高使蒸发蒸腾量减少. 高温、高 CO_2 浓度和干旱胁迫交互作用下，冬小麦净光合速率和旗叶水分含量较对照显著降低，导致产量下降 41.4%[91]. 廖建雄等[92] 研究表明，高温显著降低小麦的 N 含量，而 CO_2 浓度升高、高温和干旱三因子的复合影响则使 N 含量显著上升. Xu 等[93] 研究发现，C3 灌木和 C4 牧草的生物量在自然降水和增温

条件下增加,在干旱条件下大幅下降,CO_2 浓度升高能够部分缓解高温和干旱的负效应. Abdelgawad 等[94]认为,增温加剧了干旱对豆类植物的胁迫,而 CO_2 浓度升高效应则减小了这种影响. Lobell 等[95]应用改进的 APSIM 模型对澳大利亚东北部的高粱和小麦生长的研究表明,在未来半个世纪 CO_2 浓度升高的条件下,干旱较高温导致的平均产量下降幅度更大,但高温带来的效应也不能忽视.因此,在作物育种工作中应当加强对干旱和高温环境中的耐旱、耐热型作物品种的选育.

5 研究展望

由于人类活动等对气候系统的影响,预计未来地面气温、CO_2 浓度将持续增加,干湿地区之间和干湿季节之间的降水差异将会增大[1].这些气候因子的变化必然会对作物的生长发育和产量产生影响.前人有关作物对气候因子的响应研究较为深入,已经探索出一些可靠的研究方法并解决了某些机理性的问题.地面气温、CO_2 浓度和降水等气候因子对作物生长发育和产量的影响是一个复杂的过程,作物对不同气候因子交互作用的响应机制仍存在一定程度的不确定性[96],这可能由于气象观测数据及气候模式数据误差及作物生长和产量观测数据(如供试材料、处理方法及试验方法等)等误差影响了人们对响应机制的认识和理解.在未来的研究中,建议加强以下几个方面的研究.

1)加强研究方法和试验设备的更新.与国外的研究相比,国内对于综合气候因子的影响研究相对薄弱.迄今为止,关于多气候因子交互作用对作物影响的试验设备主要集中在人工气候箱、OTC(Open Top Chambers)、FACE、FATI(Free Air Temperature Increase)等设备上.今后此领域的研究要注意研究方法和试验设备的更新,为全球变化区域层次的集成研究提供方法上的保障.

2)加强试验研究的长期观测.作物对不同气候因子交互作用响应的试验往往由于维护费用高等原因采取短期试验,形成较多复杂对立的结论,很多作物对气候变化响应的生理机制尚未形成定论,因此有必要进行长期、连续的观测试验进行验证,从而获得稳定的结果和规律性的结论.仅通过一季、两季的试验不能充分彻底地掌握 CO_2 浓度增加和气候变化对作物的真实影响,要取得更符合实际的科学结论需要开展连续、系列的模拟试验[97].

3)提高模型模拟的准确性并对其进行试验验证.应用作物模型模拟气候变化对作物影响时还存在很大的不确定性.这些不确定性来源于:①应用气候模式数据的误差,建议尝试采用多模式集合模拟结果,以减小模型输入气候数据的不确定性;②模型初始输入数据的误差;③作物模型本身的局限性等[98-99].另外,关于气候变化对作物影响的模型模拟缺少试验验证,还需要进一步研究.

4)加强极端气候对作物影响的研究.近年来,在全球变暖的背景下,部分极端天气气候事件发生的频率与强度呈现明显变化,高温、冷害、寒害、冻害、暴雨、干旱等极端天气事件及其诱发的自然灾害必然会对作物生产造成影响.探讨和评价极端气候及其交互作用对作物生长发育及产量的影响,对于避免或减少极端气候造成的粮食产量损失具有重要意义.

参考文献

[1] Intergovernmental Panel on Climate Change. Climate Change 2013. The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 2013

[2] Intergovernmental Panel on Climate Change. The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 2007

[3] Easterling DR, Evans JL, Groisman PY, *et al*. Observed variability and trends in extremeclimate events: A brief review. *Bulletin of the American Meteorological Society*, 2000, **81**: 417-425

[4] Karl TR, Trenberth KE. Modern global climate change. *Science*, 2003, **302**: 1719-1723

[5] Qin D-H (秦大河), Ding Y-H (丁一汇), Su J-L (苏纪兰). Assessment of Climate and Environment Changes in China (I): Climate and Environment Changes in China and Their Projection. Beijing: Science Press, 2005 (in Chinese)

[6] Ren GY, Ding YH, Zhao ZC, *et al*. Recent progress in studies of climate change in China. *Advances in Atmospheric Sciences*, 2012, **29**: 958-977

[7] Wallace JS. Increasing agricultural water use efficiency to meet future food production. *Agriculture, Ecosystems and Environment*, 2000, **82**: 105-119

[8] Tao FL, Zhang Z. Impacts of climate change as a function of global mean temperature, maize productivity and water use in China. *Climatic Change*, 2011, **105**: 409-432

[9] Tokatlidis IS. Adapting maize crop to climate change. *Agronomy for Sustainable Development*, 2013, **33**: 63-79

[10] Chen X (陈　雄), Wu D-X (吴冬秀), Wang G-X

(王根轩). Effect of elevated CO_2 concentration on photosynthesis and antioxidative enzyme activities of wheat plant grown under drought condition. *Chinese Journal of Applied Ecology* (应用生态学报), 2000, **11**(6): 881-884 (in Chinese)

[11] Xu Y-C (徐仰仓), Wang J (王　静), Lin J-S (林久生), *et al*. Effect of osmotic stress on wheat membrane injury under different CO_2 concentrations. *Chinese Journal of Applied Ecology* (应用生态学报), 2000, **11** (6): 878-880 (in Chinese)

[12] Xu ZZ, Jiang YL, Zhou GS. Response and adaptation of photosynthesis, respiration, and antioxidant systems to elevated CO_2 with environmental stress in plants. *Frontiers in Plant Science*, 2015, **6**: 701, doi:10.3389/fpls.2015.00701

[13] Long SP, Ainsworth EA, Leakey ADB, *et al*. Food for thought: Lower-than-expected crop yield stimulation with rising CO_2 concentrations. *Science*, 2006, **312**: 1918-1921

[14] Reddy AR, Rasineni GK, Raghavendra AS. The impact of global elevated CO_2 concentration on photosynthesis and plant productivity. *Current Science*, 2010, **99**: 46-57

[15] Lee JS. Combined effect of elevated CO_2 and temperature on the growth and phenology of two annual C3 and C4 weedy species. *Agriculture*, *Ecosystems & Environment*, 2011, **140**: 484-491

[16] Xu ZZ, Shimizu H, Yagasaki Y, *et al*. Interactive effects of elevated CO_2, drought, and warming on plants. *Journal of Plant Growth Regulation*, 2013, **32**: 692-707

[17] Wang H-L (王鹤龄). Effects of Warming and Precipitation on Spring Wheat in the Semi-arid Region, and Response of Crop Layout on Regional Climate Change. PhD Thesis. Lanzhou: Gansu Agricultural University, 2013 (in Chinese)

[18] Zhang B-B (张蓓蓓). The Response of Water-use Efficiency to Drought, High Temperature, Fungal Inoculation and Other Environments. PhD Thesis. Yangling: Northwest A&F University, 2011 (in Chinese)

[19] Liu R-X (刘瑞侠), Li Y-H (李艳辉), Chen S-N (陈绍宁), *et al*. Effects of collaborative stress of drought and high temperature on antioxidant defense system in maize. *Journal of Henan Agricultural University* (河南农业大学学报), 2008, **42**(4): 363-366 (in Chinese)

[20] Zhou P (周　平). The possible influence of global climate changes on agricultural production in China and countermeasures. *Journal of Yunnan Agricultural University* (云南农业大学学报), 2001, **16**(1): 1-4 (in Chinese)

[21] Crafts-Brandner SJ, Salvucci ME. Sensitivity of photosynthesis in a C4 plant, maize, to heat stress. *Plant Physiology*, 2002, **129**: 1773-1780

[22] Zhang J-W (张吉旺), Dong S-T (董树亭), Wang K-J (王空军), *et al*. Effects of high field temperature on summer maize grain yield and quality. *Chinese Journal of Applied Ecology* (应用生态学报), 2007, **18**(1): 52-56 (in Chinese)

[23] Wang H-L (王鹤龄), Zhang Q (张　强), Wang R-Y (王润元), *et al*. Effects of air temperature increase and precipitation change on grain yield and quality of spring wheat in semiarid area of Northwest China. *Chinese Journal of Applied Ecology* (应用生态学报), 2015, **26** (1): 67-75 (in Chinese)

[24] Dekov I, Tsonev T, Yordanov I. Effects of water stress and high-temperature stress on the structure and activity of photosynthetic apparatus of *Zea mays* and *Helianthus annuus*. *Photosynthetica*, 2001, **38**: 361-366

[25] Hassan IA. Effects of water stress and high temperature on gas exchange and chlorophyll fluorescence in *Triticum aestivum* L. *Photosynthetica*, 2006, **44**: 312-315

[26] Lawlor DW. Limitation to photosynthesis in water-stressed leaves: Stomata vs. metabolism and the role of ATP. *Annals of Botany*, 2002, **89**: 871-885

[27] Meng F-C (孟凡超), Zhang J-H (张佳华), Hao C (郝　翠), *et al*. Effects of elevated CO_2 and different irrigation on photosynthetic parameters and yield of maize in Northeast China. *Acta Ecologica Sinica* (生态学报), 2015, **35**(7): 2126-2135 (in Chinese)

[28] Zhang B (张　斌), Zhang T-L (张桃林), Zhao Q-G (赵其国). Relationship between water potentials of red soil and crop leaves under five farming systems and their responses to drought stress in dry season. *Acta Pedologica Sinica* (土壤学报), 1999, **36**(1): 101-110 (in Chinese)

[29] Schlenker W, Lobell DB. Robust negative impacts of climate change on African agriculture. *Environmental Research Letters*, 2010, **5**: 014010

[30] Jones PG, Thornton PK. The potential impacts of climate change on maize production in Africa and Latin America in 2055. *Global Environmental Change*, 2003, **13**: 51-59

[31] Wang W-D (王伟东), Wang P (王　璞), Wang Q-X (王启现). Effects of thermal stress and water deficit on kernel set and kernel weight during filling in maize (*Zea mays* L.). *Journal of Heilongjiang August First Land Reclamation University* (黑龙江八一农垦大学学报), 2001, **13**(2): 19-24 (in Chinese)

[32] Craufurd PQ, Peacock JM. Effect of heat and drought stress on sorghum (*Sorghum bicolor*). II. Grain yield. *Experimental Agriculture*, 1993, **29**: 77-86

[33] Wu H-L (吴宏亮), Zhou X-L (周续莲), Kang J-H (康建宏). Progress on starch formation under the high temperature and drought after blossom of wheat. *Journal of Agricultural Sciences* (农业科学研究), 2011, **32** (3): 67-71 (in Chinese)

[34] Moradi R, Koocheki Al, Mahallati MN, *et al*. Adaptation strategies for maize cultivation under climate change in Iran: Irrigation and planting date management. *Mitigation & Adaptation Strategies for Global Change*, 2013, **18**: 265-284

[35] Wang Q (王　琪), Ma S-Q (马树庆), Guo J-P (郭建平), *et al*. Effects of air temperature on maize growth and its yield. *Chinese Journal of Ecology* (生态学杂

志), 2009, **28**(2): 255-260 (in Chinese)

[36] Wang X-L (王修兰), Xu S-H (徐师华), Cui D-C (崔读昌). The diagnosis and estimation of CO_2 concentration increasing and climate warming on the agricultural production. *Chinese Journal of Eco-Agriculture* (中国生态农业学报), 2003, **11**(4): 47-48 (in Chinese)

[37] Leakey ADB, Ainsworth EA, Bernacchi CJ, *et al*. Elevated CO_2 effects on plant carbon, nitrogen, and water relations: Six important lessons from FACE. *Journal of Experimental Botany*, 2009, **60**: 2859-2876

[38] Kang SZ, Zhang FC, Hu XT, *et al*. Benefits of CO_2 enrichment on crop plants are modified by soil water status. *Plant and Soil*, 2002, **238**: 69-77

[39] Markelz RJC, Strellner RS, Leakey ADB. Impairment of C4 photosynthesis by drought is exacerbated by limiting nitrogen and ameliorated by elevated [CO_2] in maize. *Journal of Experimental Botany*, 2011, **62**: 3235-3246

[40] Manderscheid R, Erbs M, Weigel HJ. Interactive effects of free-air CO_2 enrichment and drought stress on maize growth. *European Journal of Agronomy*, 2014, **52**: 11-21

[41] Zong YZ, Wang WF, Xue QW, *et al*. Interactive effects of elevated CO_2 and drought on photosynthetic capacity and PSII performance in maize. *Photosynthetica*, 2014, **52**: 63-70

[42] Mauney JR, Fry KE, Guinn G. Relationship of photosynthetic rate to growth and fruiting of cotton, soybean, sorghum, and sunflower. *Crop Science*, 1978, **18**: 259-263

[43] Ellis RH, Craufurd PQ, Summerfield RJ, *et al*. Linear relations between carbon dioxide concentration and rate of development towards flowering in sorghum, cowpea and soybean. *Annals of Botany*, 1995, **75**: 193-198

[44] Cure JD, Acock B. Crop responses to carbon dioxide doubling: A literature survey. *Agricultural and Forest Meteorology*, 1986, **38**: 127-145

[45] Shi Y-H (石耀辉), Zhou G-S (周广胜), Jiang Y-L (蒋延玲), *et al*. Effects of interactive CO_2 concentration and precipitation on growth characteristics of *Stipa breviflora*. *Acta Ecologica Sinica* (生态学报), 2013, **33**(14): 4478-4485 (in Chinese)

[46] Li F-S (李伏生), Kang S-Z (康绍忠), Zhang F-C (张富仓). Effects of CO_2 enrichment, nitrogen and water on photosynthesis, evapotranspiration and water use efficiency of spring wheat. *Chinese Journal of Applied Ecology* (应用生态学报), 2003, **14**(3): 387-393 (in Chinese)

[47] Wall GW, Garcia RL, Kimball BA, *et al*. Interactive effects of elevated carbon dioxide and drought on wheat. *Agronomy Journal*, 2006, **98**: 354-381

[48] Wall GW, Brooks TJ, Adam NR, *et al*. Elevated atmospheric CO_2 improved Sorghum plant water status by ameliorating the adverse effects of drought. *New Phytologist*, 2001, **152**: 231-248

[49] Wall GW, Garcia RL, Wechsung F, *et al*. Elevated atmospheric CO_2 and drought effects on leaf gas exchange properties of barley. *Agriculture, Ecosystems & Environment*, 2011, **144**: 390-404

[50] Woodwell GM. The warming of the industrialized middle latitudes 1985 - 2050: Causes and consequences. *Climate Change*, 1989, **15**: 31-50

[51] Murray DR. Plant responses to carbon dioxide. *American Journal of Botany*, 1989, **82**: 690-697

[52] Ainsworth EA, Rogers A. The response of photosynthesis and stomatal conductance to rising [CO_2]: Mechanisms and environmental interactions. *Plant, Cell and Environment*, 2007, **30**: 258-270

[53] Curtis PS, Wang XZ. A meta-analysis of elevated CO_2 effects on woody plant mass, form, and physiology. *Oecologia*, 1998, **113**: 299-313

[54] Cure JD. Carbon dioxide doubling responses: A crop survey// Strain BR, Cure JD, eds. Direct Effects of Increasing Carbon Dioxide on Vegetation. Washington DC: Office of Basic Energy Science, U.S. Department of Energy, 1985: 99-116

[55] Meng F-C (孟凡超), Zhang J-H (张佳华), Yao F-M (姚凤梅). Interactive effects of elevated [CO_2] and increasing precipitation on yield and growth characters of maize. *Chinese Journal of Plant Ecology* (植物生态学报), 2014, **38**(10): 1064-1073 (in Chinese)

[56] Xu L (徐　玲), Zhao T-H (赵天宏), Hu Y-Y (胡莹莹), *et al*. Effects of CO_2 enrichment on photosynthesis and grain yield of spring wheat. *Journal of Triticeae Crops* (麦类作物学报), 2008, **28**(5): 867-872 (in Chinese)

[57] Wang R-J (王润佳), Zhang X-C (张绪成), Gao S-M (高世铭), *et al*. Effects of atmospheric CO_2 enrichment and nitrogen application rate on photosynthetic parameters and water use efficiency of spring wheat. *Agricultural Research in the Arid Aeras* (干旱地区农业研究), 2010, **28**(5): 32-37 (in Chinese)

[58] Allen Jr LH, Kakani VG, Vu JCV, *et al*. Elevated CO_2 increases water use efficiency by sustaining photosynthesis of water-limited maize and sorghum. *Journal of Plant Physiology*, 2011, **168**: 1909-1918

[59] Wang J-L (王建林), Wen X-F (温学发), Zhao F-H (赵风华), *et al*. Effects of doubled CO_2 concentration on leaf photosynthesis, transpiration and water use efficiency of eight crop species. *Chinese Journal of Plant Ecology* (植物生态学报), 2012, **36**(5): 438-446 (in Chinese)

[60] Idso KE, Idso SB. Plant responses to atmospheric CO_2 enrichment in the face of environmental constraints: A review of the past 10 years' research. *Agricultural and Forest Meteorology*, 1994, **69**: 153-203

[61] Ottman MJ, Kimball BA, Pinter PJ, *et al*. Elevated CO_2 increases sorghum biomass under drought conditions. *New Phytologist*, 2001, **50**: 261-273

[62] Leakey ADB, Uribelarrea M, Ainsworth EA, *et al*. Photosynthesis, productivity, and yield of maize are not affected by open-air elevation of CO_2 concentration in the absence of drought. *Plant Physiology*, 2006, **140**: 779-790

[63] Amthor JS, Mitchell RJ, Brett Runion G, *et al*. Energy

content, construction cost and phytomass accumulation of *Glycine max* (L.) Merr. and *Sorghum bicolor* (L.) Moench grown in elevated CO_2 in the field. *New Phytologist*, 1994, **128**: 443-450

[64] Reeves DW, Rogers HH, Prior SA, *et al*. Elevated atmospheric carbon dioxide effects on sorghum and soybean nutrient status. *Journal of Plant Nutrition*, 1994, **17**: 1939-1954

[65] Meng FC, Zhang JH, Yao FM, *et al*. Interactive effects of elevated CO_2 concentration and irrigation on photosynthetic parameters and yield of maize in Northeast China. *PLoS One*, 2014, **9**(5): e98318

[66] Guo J-P (郭建平), Gao S-H (高素华). The experimental study on impacts of high temperature and high CO_2 concentration on crops. *Chinese Journal of Eco-Agriculture* (中国生态农业学报), 2002, **10**(1): 17-20 (in Chinese)

[67] Su Y (苏　营), Zhang Y-F (张逸飞), Mou W-Y (牟文雅), *et al*. Morphological traits and yield of soybean under elevated atmospheric CO_2 concentration and temperature. *Acta Ecologica Sinica* (生态学报), 2016, **36**(9): 2597-2606 (in Chinese)

[68] Kim SH, Gitz DC, Sicher RC, *et al*. Temperature dependence of growth, development, and photosynthesis in maize under elevated CO_2. *Environmental and Experimental Botany*, 2007, **61**: 224-236

[69] Lai S-K (赖上坤), Zhuang S-T (庄时腾), Wu Y-Z (吴艳珍), *et al*. Impact of elevated atmospheric CO_2 concentration and temperature on growth and development of super rice. *Chinese Journal of Ecology* (生态学杂志), 2015, **34**(5): 1253-1262 (in Chinese)

[70] Conroy JP, Seneweera S, Basra AS, *et al*. Influence of rising atmospheric CO_2 concentrations and temperature on growth, yield and grain quality of cereal crops. *Australian Journal of Plant Physiology*, 1994, **21**: 741-758

[71] Alonso A, Perez P, Martinez-Carrasco R. Growth in elevated CO_2 enhances temperature response of photosynthesis in wheat. *Physiologia Plantarum*, 2009, **135**: 109-120

[72] Zhou X, Ge ZM, Kellomaki S, *et al*. Effects of elevated CO_2 and temperature on leaf characteristics, photosynthesis and carbon storage in aboveground biomass of a boreal bioenergy crop (*Phalaris arundinacea* L.) under varying water regimes. *Global Change Biology Bioenergy*, 2011, **3**: 223-234

[73] He JS, Wolfe-Bellin KS, Bazzaz FA. Leaf-level physiology, biomass, and reproduction of *Phytolacca americana* under conditions of elevated CO_2 and altered temperature regimes. *International Journal of Plant Sciences*, 2005, **166**: 615-622

[74] Clifford SC, Stronach IM, Black CR, *et al*. Effects of elevated CO_2, drought and temperature on the water relations and gas exchange of groundnut (*Arachis hypogaea*) stands grown in controlled environment glasshouses. *Physiologia Plantarum*, 2000, **110**: 78-88

[75] Lin W-H (林伟宏), Bai K-Z (白克智), Kuang T-Y (匡廷云). Effects of elevated CO_2 and high temperature on single leaf and canopy photosynthesis of rice. *Acta Botanica Sinica* (植物学报), 1999, **41**(6): 624-628 (in Chinese)

[76] de Souza AP, Gaspar M, Da Silva EA, *et al*. Elevated CO_2 increases photosynthesis, biomass and productivity, and modifies gene expression in sugarcane. *Plant, Cell & Environment*, 2008, **31**: 1116-1127

[77] Burkart S, Manderscheid R, Wittich KP, *et al*. Elevated CO_2 effects on canopy and soil water flux parameters measured using a large chamber in crops grown with free-air CO_2 enrichment. *Plant Biology*, 2011, **13**: 258-269

[78] Prior SA, Runion GB, Marble SC, *et al*. A review of elevated atmospheric CO_2 effects on plant growth and water relations, implications for horticulture. *HortScience*, 2011, **46**: 158-162

[79] Tan K-Y (谭凯炎), Zhou G-S (周广胜), Ren S-X (任三学). Response of leaf dark respiration of winter wheat to changes in CO_2 concentration and temperature. *Chinese Science Bulletin* (科学通报), 2013, **58**(12): 1158-1163 (in Chinese)

[80] Kim HY, Lim SS, Kwak JH, *et al*. Dry matter and nitrogen accumulation and partitioning in rice (*Oryza sativa* L.) exposed to experimental warming with elevated CO_2. *Plant and Soil*, 2011, **342**: 59-71

[81] Nam HS, Kwak JH, Lim SS, *et al*. Fertilizer N uptake of paddy rice in two soils with different fertility under experimental warming with elevated CO_2. *Plant and Soil*, 2013, **369**: 563-575

[82] Zhou C (周　超), Liu S-W (刘树伟), Zhang L (张令), *et al*. Effect of elevated CO_2 and temperature on CH_4 emissions from rice paddy fields: A T-FACE experiment. *Journal of Agro-Environment Science* (农业环境科学学报), 2013, **32**(10): 2077-2083 (in Chinese)

[83] De Costa WAJM, Weerakoon WMW, Herath HMLK, *et al*. Physiology of yield determination of rice under elevated carbon dioxide at high temperatures in a subhumid tropical climate. *Field Crops Research*, 2006, **98**: 336-347

[84] Heinemann AB, Maia AHN, Dourado-Neto D, *et al*. Soybean (*Glycine max* (L.) Merr.) growth and development response to CO_2 enrichment under different temperature regimes. *European Journal of Agronomy*, 2006, **24**: 52-61

[85] Wheeler TR, Hong TD, Ellis RH, *et al*. The duration and rate of grain growth, and harvest index of wheat (*Triticum aestivum* L.) in response to temperature and CO_2. *Journal of Experimental Botany*, 1996, **47**: 623-630

[86] Lal M, Singh KK, Rathore LS, *et al*. Vulnerability of rice and wheat yields in NW India to future changes in climate. *Agricultural and Forest Meteorology*, 1998, **89**: 101-114

[87] Li G (李　广), Li Y (李　玥), Huang G-B (黄高宝), *et al*. Response of dryland spring wheat yield to elevated CO_2 concentration and temperature by APSIM model. *Chinese Journal of Eco-Agriculture* (中国生态农

业学报), 2012, **20**(8): 1088-1095 (in Chinese)

[88] Ruiz-Vera UM, Siebers MH, Drag DW, *et al*. Canopy warming caused photosynthetic acclimation and reduced seed yield in maize grown at ambient and elevated [CO_2]. *Global Change Biology*, 2015, **21**: 4237-4249

[89] Yang P, Wu W, Li Z, *et al*. Simulated impact of elevated CO_2, temperature, and precipitation on the winter wheat yield in the North China Plain. *Regional Environmental Change*, 2014, **14**: 61-74

[90] Liao J-X (廖建雄), Wang G-X (王根轩). Effects of drought, CO_2 concentration and temperature increasing on photosynthesis rate, evapotranspiration, and water use efficiency of spring wheat. *Chinese Journal of Applied Ecology* (应用生态学报), 2002, **13**(5): 547-550 (in Chinese)

[91] Si F-Y (司福艳), Qiao Y-Z (乔匀周), Jiang J-W (姜净卫), *et al*. Effects of drought stress, high temperature and elevated CO_2 concentration on the growth of winter wheat. *Chinese Journal of Applied Ecology* (应用生态学报), 2014, **25**(9): 2605-2612 (in Chinese)

[92] Liao J-X (廖建雄), Wang G-X (王根轩). The effects of increasing CO_2, temperature and drought on the chemical composition of wheat leaves. *Acta Phytoecologica Sinica* (植物生态学报), 2000, **24**(6): 744-747 (in Chinese)

[93] Xu ZZ, Shimizu H, Ito S, *et al*. Effects of elevated CO_2, warming and precipitation change on plant growth, photosynthesis and peroxidation in dominant species from North China grassland. *Planta*, 2014, **239**: 421-435

[94] Abdelgawad H, Farfan-Vignolo ER, de Vos D, *et al*. Elevated CO_2 mitigates drought and temperature-induced oxidative stress differently in grasses and legumes. *Plant Science*, 2015, **231**: 1-10

[95] Lobell DB, Hammer GL, Chenu K, *et al*. The shifting influence of drought and heat stress for crops in northeast Australia. *Global Change Biology*, 2015, **21**: 4115-4127

[96] Xiao G-J (肖国举), Zhang Q (张　强), Wang J (王静). Impact of global climate change on agro-ecosystem: A review. *Chinese Journal of Applied Ecology* (应用生态学报), 2007, **18**(8): 1877-1885 (in Chinese)

[97] Xie L-Y (谢立勇), Ma Z-Y (马占云), Gao X-N (高西宁), *et al*. FACE and its limitations on researches of impacts of elevated CO_2 on crops. *Journal of China Agricultural University* (中国农业大学学报), 2008, **13**(3): 23-28 (in Chinese)

[98] Xiong W (熊　伟), Xu Y-L (许吟隆), Lin E-D (林而达), *et al*. Simulation experiment of RCM and crop model combination and its uncertainty assessment. *Chinese Journal of Ecology* (生态学杂志), 2005, **24**(7): 741-746 (in Chinese)

[99] Yao FM, Qin PC, Zhang JH, *et al*. Uncertainties in assessing the effect of climate change on agriculture using model simulation and uncertainty processing methods. *Chinese Science Bulletin*, 2011, **56**: 729-737

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Meng F-C, Guo J, Zhou L, *et al*. Interactive effects of temperature, CO_2 concentration and precipitation on growth and yield of crops. *Chinese Journal of Applied Ecology*, 2017, **28**(12): 4117-4126 (in Chinese)