How will ecosystems respond to global warming?

粮食作物产量对气候变暖的响应

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摘要 玉米、小麦和水稻是主要粮食作物, 总收获面积和总产量分别占全球禾谷类作物的79%和90%。气候变暖导致主要粮食作物减产。玉米对气候变暖的敏感性高于小麦, 温度升高1℃导致全球玉米减产3%~12%, 小麦减产3%~9%; 温度升高有利于中、高纬度地区水稻生产, 但导致低纬度地区水稻减产。作物产量对气候变暖的响应呈非线性, 当温度高于作物生长的适宜温度时, 产量对气候变暖的敏感性随温度升高的幅度进一步增强。热带地区作物产量对气候变暖的敏感性高于温带地区; 雨养农业区作物产量对气候变暖的敏感性高于灌溉农业区, 灌溉可有效降低高温对作物产量的负面影响。大气CO₂浓度升高促进作物生长, CO₂施肥效应能在一定程度上补偿由于气候变暖导致的粮食作物减产。气候变暖导致粮食作物减产以及CO₂浓度升高促进作物生长已有共识, 但对气候变暖下CO₂施肥效应的认知存在极大的不足, 其主要原因是自然状态下CO₂浓度升高和增温对作物生长的交互作用的实验研究太少。未来研究重点应拓展FACE(free-air CO₂ enrichment)条件下的增温实验, 通过不同CO₂浓度梯度下的增温实验, 结合其他因子(水分、氮素等)的调控, 精细量化不同条件下的CO₂施肥效应, 并据此发展和完善作物模型, 进而客观评估未来气候变暖情景下CO₂的施肥效应及其对作物减产的补偿作用。

关键词 作物产量, 气候变暖, 温度敏感性, CO₂施肥效应, 交互作用

民以食为天。2017年全球人口75.5亿, 预计到2050年和2100年将先后增加到94~102亿和96~132亿^[1]。至21世纪中叶, 全球粮食产量至少要在2006年的基础上增加60%, 方能满足日趋增长的人口对食品的需求^[2]。玉米、小麦和水稻是主要的粮食作物, 总收获面积和总产量分别占全球禾谷类作物的79%和90%(<http://www.fao.org/faostat/en/#data/QC>)。1880~2012年, 全球平均温度升高了0.85℃; 1951~2012年, 全球的升温速率为每十年0.12℃^[3]。与1986~2005年相比, 21世纪中期和后期全球平均温度可能升高1~2℃和1~3.7℃, 且2100年之后仍将持续变暖^[3]。1980~2008年间, 气候变化导致全球玉米减产3.8%, 小麦减产2.5%, 水稻增产2.9%^[4]。到21世纪中叶, 气

候变化可能导致全球作物减产10%左右^[5~7]。

1 粮食作物产量对气候变暖的敏感性

玉米种植面积最大的4个国家分别是中国、美国、巴西和印度, 占全球种植面积的52%; 小麦种植面积最大的4个国家分别是印度、中国、俄罗斯和美国, 占全球种植面积的44%; 水稻种植面积最大的4个国家分别是印度、中国、印度尼西亚和孟加拉国, 占全球种植面积的61%(<http://www.fao.org/faostat/en/#data/QC>)。

以温度升高1℃下作物产量变化的百分比作为温度敏感性指标^[8,9]。在全球尺度上, 玉米对气候变暖的敏感性高于小麦, 温度升高1℃导致全球玉米减产

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约8%，小麦减产约6%^[9~11](表1)。热带地区作物产量对气候变暖的敏感性高于温带地区，升温1℃导致热带地区玉米和小麦减产5%~12%，温带地区减产小于5%^[5]。在国家尺度上，中国玉米产量对气候变暖的

敏感性与全球相仿，但高于巴西和印度(表1)；Lobell等人^[4]采用统计模型的研究结果显示，温度升高1℃对印度的玉米产量无显著影响，但Zhao等人^[11]采用4种方法的最新研究结果表明，升温1℃导致印度玉米

表1 玉米、小麦和水稻产量对升温1℃的响应^{a)}

Table 1 Response of maize, wheat and rice yields to 1℃ warming

作物	全球或国家	研究时段	产量变化(%)	文献
玉米	全球	1961~2002年	-8.3 (-4.0, -12.2)	[10]
	全球	1981~2010年	-7.4 (-2.9, -11.9)	[11]
	中国	1980~2008年	-5.7 (-2.6, -8.7)	[4]
	中国	1981~2010年	-8.0 (-1.9, -14.1)	[11]
	中国	1980~2008年	-8.8 (-7.2, -10.5)	[12]
	美国	1980~2008年	-4.3 (-2.1, -6.5)	[4]
	美国	1981~2010年	-10.3 (-4.9, -15.7)	[11]
	巴西	1980~2008年	-5.0 (-2.1, -7.9)	[4]
	巴西	1981~2010年	-5.5 (-1.0, -10.0)	[11]
	印度	1980~2008年	0.1 (-4.8, +4.9)	[4]
	印度	1981~2010年	-5.2 (-0.7, -9.7)	[11]
小麦	全球	1981~2010年	-6.0 (-4.2, -8.2)	[9]
	全球	1961~2002年	-5.4 (-3.2, -8.4)	[10]
	全球	1981~2010年	-6.0 (-3.1, -8.9)	[11]
	全球	1981~2010年	-6.0 (-4.0, -8.0)	[13]
	中国	1980~2008年	-1.3 (-2.6, +0.1)	[4]
	中国	1981~2010年	-2.6 (-5.7, +0.5)	[11]
	中国	1980~2008年	-2.9 (-0.9, -5.2)	[12,13]
	美国	1980~2008年	-4.6 (-2.7, -6.5)	[4]
	美国	1981~2010年	-5.5 (-1.1, -9.9)	[11]
	美国	1981~2010年	-7.6 (-5.0, -10.2)	[13]
	俄罗斯	1980~2008年	-10.7 (-7.2, -14.1)	[4]
	俄罗斯	1981~2010年	-7.8 (-1.5, -14.1)	[11]
	俄罗斯	1981~2010年	-4.7 (-2.5, -6.8)	[13]
	印度	1980~2008年	-8.1 (-4.6, -11.5)	[4]
	印度	1981~2010年	-9.1 (-3.7, -14.5)	[11]
	印度	1980~2010年	-7.8 (-4, -13.1)	[13,14]
水稻	全球	1961~2002年	-0.6 (-1.9, +0.9)	[10]
	全球	1981~2010年	-3.2 (-6.9, +0.5)	[11]
	中国	1980~2008年	+2.0 (-0.5, +4.5)	[4]
	中国(单季稻)	1961~2010年	+4.6 (+0.1, +9.2)	[15]
	中国(双季稻)	1961~2010年	-2.8 (-6.0, +0.5)	[15]
	印度	1980~2008年	-7.8 (-2.1, -13.5)	[4]
	印度	1981~2010年	-6.6 (-2.8, -10.4)	[11]
	印度	1980~2010年	-5	[14]
	印度尼西亚	1980~2008年	+0.4 (-2.4, +3.1)	[4]
	孟加拉国	1980~2008年	-0.3 (-4.7, +4.1)	[4]

a) 产量变化指单产变化或收获面积不变的总产量变化，括号内数值为不确定性范围

减产5%。印度和俄罗斯小麦产量对气候变暖的敏感性高于美国,中国最低(表1)。水稻为喜温作物,气候变暖对全球尺度的水稻产量影响甚微^[4,10],但存在明显的区域差异。温度升高有利于中、高纬度地区水稻生产,但导致低纬度地区水稻减产^[16]。升温1℃导致印度水稻减产5%~8%,中国双季稻减产2.8%,单季稻增产4.6%,对印度尼西亚和孟加拉国水稻产量无显著影响(表1)。

雨养农业区作物产量对气候变暖的敏感性高于灌溉农业区,灌溉可有效减少高温对作物产量的负面影响^[17]。印度小麦产地主要分布于西北部干旱少雨的地区,每年10~11月播种,翌年2~4月收获,以雨养农业为主;中国小麦主产区以灌溉农业为主。升温1℃导致印度小麦减产8%~9%,但中国仅减产1%~3%(表1)。在非洲玉米生长季平均温度高于25℃的区域,温度升高1℃可导致玉米减产20%以上,但具有灌溉条件的地区只减产10%左右^[18];美国东部雨养区玉米产量对气候变暖的敏感性亦高于西部灌溉区^[19]。

作物产量对气候变暖的响应呈非线性。当温度低于(高于)作物生长的适宜温度时,温度升高增加(降低)作物产量^[18~21]。当温度高于作物生长的适宜温度时,作物产量对气候变暖的敏感性随温度升高的幅度进一步增强^[18,19]。适度升温有助于提高中、高纬度地区的作物产量,但低纬度地区减产明显^[22]。升温1~2℃明显降低热带地区的玉米和小麦产量,对温带地区无显著影响或略有增产,但升温3~5℃则显著降低温带地区这两种作物的产量^[22]。温度升高1, 2和3℃可能导致印度水稻减产5.4%, 7.4%和25.1%^[23]。

2 大气CO₂浓度升高的补偿作用与不确定性

绿色植物通过光合作用将大气CO₂转化为储存能量的有机物质,提供给人类生存所必须的粮食、油和纤维等。伴随大气CO₂浓度升高和全球温暖化趋势加剧,各国科学家广泛关注CO₂的施肥效应(CO₂ fertilization effect, CFE),即大气CO₂浓度增加对植物生长或生产力的促进作用,以期CO₂的施肥效应能在一定程度上补偿由于气候变暖导致的粮食作物减产^[24,25]。

未来大气CO₂浓度增加对作物减产的补偿作用似乎是乐观的。模型模拟显示,到21世纪中叶,若不考虑种植面积变化和品种更新,气候变化可能导致

全球玉米、小麦和水稻等11种作物减产0~13%,若考虑大气CO₂升高的施肥效应,则可能增产8%~22%^[26]或禾谷类作物不减产^[27]。雨养农业的CFE高于灌溉农业^[28], C₃作物的CFE高于C₄作物^[20,29,30]。在高温温室气体排放情景(RCP8.5)下,即21世纪末大气CO₂浓度达936 ppm(1 ppm=1 μL/L,下同),全球气温上升2.6~4.8℃^[3],小麦仍可增产3.2%,玉米和水稻则分别减产8.5%和2.9%^[31]。虽然对大气CO₂浓度升高的施肥效应具有广泛的共识,但不同研究者的模型估计结果存在极大的差异(表2)。在A2情景下, Fischer^[27]估计21世纪50年代雨养玉米可能增产2%~6%(无CO₂施肥效应)和6%~10%(有CO₂施肥效应),但 Nelson 等人^[28]的估计值则分别为-5.7%~+0.6%和-0.8%~+9.5%(表2)。不同研究者估计的CFE也大相径庭, McGrath 和 Lobell^[34]估计,大气CO₂浓度增加100 ppm,全球作物产量增加5%~17%;按照 Müller 等人^[26]和 Fischer^[27]的模拟结果,大气CO₂浓度增加100 ppm,全球作物产量可能增加2.4%~4.2%和8%~24%^[34]。模型估计的不确定性随CO₂浓度及温度升高而增加^[35]。

在评估气候变化影响和适应的模型中, CO₂施肥效应是模型中最不确定且极其敏感的参数^[36], CO₂施肥效应的参数化通常基于实验研究结果^[24]。自由大气CO₂浓度增高(free-air CO₂ enrichment, FACE)技术实现了自然状态下对CO₂浓度升高的控制,是研究CO₂施肥效应的理想方法^[37]。但由于FACE系统对仪器设备的投入、维护及CO₂消耗费用很高,实验数据甚少。即便如此, FACE实验得到的CO₂施肥效应^[38~43]亦显示出极大的差异,这些差异与实验点气候、土壤、氮素投入和作物品种有关。

3 结语

2000~2014年,全球主要粮食作物收获面积不断扩大(<http://www.fao.org/faostat/en/#data/QC>)。玉米、小麦和水稻收获面积的年均增长率分别为 3.64×10^4 , 0.55×10^4 和 1.10×10^4 km²/a。为满足日趋增长的人口对食品的需求,未来全球粮食作物的种植面积将继续增加^[27,28]。

气候变暖导致粮食作物减产以及CO₂浓度升高促进作物生长已有共识,但对气候变暖下CO₂施肥效应的认知存在极大的不足,其主要原因是自然状态下CO₂浓度升高和增温对作物生长的交互作用的实

表2 不同情景下气候变化对全球作物产量影响的预测^{a)}

Table 2 Projections of climate change impact on global crop yields under different scenarios

作物	气候变化情景	预测年/对照年	产量变化(%)		文献
			CC wo/CO ₂	CC w/CO ₂	
11种农作物	A1b, A2, B1	2050/2000	0~-13	+8~-22	[26]
禾谷类作物	A2	21世纪50年代/21世纪前10年	-5	0	[27]
玉米	A2 (I)	2050/2000	-1.2~-8.7	-1.2~-8.6	[28]
玉米	A2 (R)	2050/2000	-5.7~+0.6	-0.8~+9.5	[28]
玉米	A2 (R)	21世纪50年代/21世纪前10年	+2~+6	+6~+10	[27]
小麦	A2 (I)	2050/2000	-4.9~-34.3	-0.1~-27.2	[28]
小麦	A2 (R)	2050/2000	-1.4~+3.1	+8.5~+9.7	[28]
小麦	A2 (R)	21世纪50年代/21世纪前10年	-8~-10	-3~-5	[27]
水稻	A2 (I)	2050/2000	-3.5~-18.5	-0.5~+10.5	[28]
水稻	A2 (R)	2050/2000	-1.4~+17.3	+6.4~+23.4	[28]
玉米	RCP 8.5	21世纪50年代/20世纪80年代	-10.5±3.2	-7.4±3.2	[32]
玉米	RCP 8.5	2080/2000	-21.2(-13.3, -28.2)	-8.5(-16.4, +1)	[30]
小麦	RCP 8.5	2080/2000	-22.6(-14.9, -27.8)	+3.2(-0.6, +13.7)	[30]
水稻	RCP 8.5	2080/2000	-27.2(-16.3, -32.9)	-2.9(-12.3, +13.8)	[30]
玉米	+1.5℃	21世纪不同时间段/(1986~2005)	-8.4(-26, +4.5)	-1.4(-26.6, +8.0)	[33]
小麦	+1.5℃	21世纪不同时间段/(1986~2005)	-14.3(-4.9, -20.2)	+2.2(-6.1, +17.4)	[33]
水稻	+1.5℃	21世纪不同时间段/(1986~2005)	-8.4(-16.6, +4.5)	+6.8(-16.6, +24.5)	[33]
玉米	+2℃	21世纪不同时间段/(1986~2005)	-11.9 (-7.2, -33.1)	-6.1(-37.8, +2.2)	[33]
小麦	+2℃	21世纪不同时间段/(1986~2005)	-19.0(-6.1, -36.6)	-0.2(-8.4, +20.9)	[33]
水稻	+2℃	21世纪不同时间段/(1986~2005)	-15.5(-21.3, +13.9)	+6.8(-14.3, +26.8)	[33]

a) 预测的产量均不考虑收获面积变化, 括号内数值为不确定性范围. CC wo/CO₂, 无CO₂施肥效应; CC w/CO₂, 有CO₂施肥效应; A2 (I)为灌溉农业; A2 (R)为雨养农业

验研究太少^[37], 以及模型研发的局限性^[34], 这限制了我们对客观评估未来气候变暖情景下CO₂的施肥效应及其对作物减产的补偿作用. 由于缺乏不同条件下的实验数据, 以及对CO₂施肥效应与其他因素相互作用的认知不足^[22], 现有模型并未包括CO₂效应与温度、作物类型、水分状况和氮素有效性的相互作用^[34]. 此外, 大气CO₂浓度升高影响植物害虫和病原菌的分布、数量和行为^[44~46], 大多数病原体的繁殖力随着CO₂浓度的升高而增加^[47], 这必然降低CO₂的施肥效应.

虽然FACE实验是研究CO₂施肥效应的理想方法, 但这些实验都是建立在一个骤增的CO₂浓度水平下(比自由大气增加100~200 ppm), 且对同一作物的试验一般不超过3年. 自然状态下大气CO₂浓度升高是一个渐增的过程, 即便在温室气体排放非常高的情景下, 至2100年大气CO₂浓度估计为936 ppm^[3], 年均增加量也只有6.5 ppm. 当作物长期处于高浓度CO₂下时, 其叶片的光合速率会逐渐下降, 这种现象被称

为光合作用对高浓度CO₂的适应或下调^[48]. Ainsworth和Long^[29]对全球FACE实验结果的meta分析表明, C₃植物叶片最大羧化速率(V_{cmax})和最大电子传递速率(J_{max})均比自由大气条件下低, 类似结果在水稻FACE^[49]和小麦FACE^[50]的研究中也被观察到. 我们尚不清楚作物对CO₂浓度渐增和骤增的响应程度是否相同, CO₂浓度渐增条件下的CFE是否会逐渐降低.

FACE条件下的增温实验有助于理解自然状态下CO₂浓度升高和增温对作物生长及产量形成的交互作用^[37], 但这类研究甚少. 迄今国际上仅有几篇文献报道了FACE条件下增温对玉米^[42]、大豆^[51]、小麦和水稻^[52~54]产量的影响. 未来研究重点应拓展FACE条件下的增温实验, 通过不同CO₂浓度梯度下的增温实验, 结合其他因子(水分、氮素等)的调控, 精细化不同条件下的CO₂施肥效应, 为模型的发展和完善提供理论依据和数据基础, 进而客观评估未来气候变暖情景下CO₂的施肥效应及其对作物减产的补偿作用.

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Response of grain crop yields to climate warming

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World population, now 7.55 billion people, will increase to 9.4–10.2 billion in 2050 and 9.6–13.2 billion in 2100. Global food demand in 2050 is projected to increase by at least 60% above 2006 levels to meet the world's food needs for growing populations. Maize, wheat and rice are the main grain crops in the world, accounting together for approximately 90% of global cereal crop yields. Over the last six decades, global mean surface temperature increased at a rate of 0.12°C per decade. Relative to the period of 1986–2005, global surface temperature is projected to increase 1–3.7°C in the late 21st century. Climate warming has led to a reduction of grain crop yields. The sensitivity of maize to climate warming is more pronounced than that of wheat. Global yields of maize and wheat decreased by 3%–12% and 3%–9% for 1°C warming, respectively. Warming is likely beneficial to rice production in mid- and high-latitudes, but leads to loss of rice yield in low-latitude. Yield losses induced by climate warming are greater in tropical regions than in temperate regions, with the loss of 5%–12% per degree warming for tropical maize and wheat and less than 5% for temperate maize and wheat. Crop yields are more sensitive to climate warming in rain-fed agriculture than in irrigated agriculture. Irrigation can effectively reduce the negative impact of warming on crop yield. Response of crop yields to climate warming is nonlinear. The sensitivity of crop yield to climate warming is further enhanced with increasing temperature, when the temperature is above the optimum thresholds of crop growth. Elevated atmospheric CO₂ concentration could benefit crop yields by increasing photosynthesis, and thus offset the yield losses due to climate warming to some extent. The fertilization effect of rising CO₂ concentration on crop yield in the future seems optimistic from model simulations. However, there is big uncertainty in the magnitude of the CO₂ effect and the significance of interactions with other factors. A primary reason for this uncertainty is the limited availability of experimental data on CO₂ responses for crops grown under various field conditions. Moreover, no models currently account for the interactions of CO₂ with temperature, varieties, water status, and nitrogen availability. The free-air CO₂ enrichment (FACE) technique remains the best platform to test plants under the open-field conditions. The future FACE experiments should focus on the responses of crop production to various levels of elevated CO₂ and interactions with warmer temperature, water status and nitrogen input. The uncertainties in CO₂ fertilization effect could be reduced when the field experiments are largely expanded. Furthermore, improving temperature and CO₂ relationships in models is essential to precisely assess the CO₂ fertilization effect at regional and/or global scales.

crop yield, climate warming, sensitivity to temperature change, CO₂ fertilization effect, interactions

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