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全球视角:转基因作物与生物多样性

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摘　要　自然界中基因的横向转移广泛存在,转基因技术即是模仿自然界中的基因横向转移。在转基因技术开发和测试长达 30 多年之后,这一技术已被用于生产种类繁多的药物、几乎全世界所消费的啤酒和奶酪以及 27 个国家的 1 800 万农民在 1.75 亿 hm^2 土地上种植的农作物。数以亿计的人和数十亿的家畜消费这些转基因作物及其制品差不多 20 年了,但是没有来自任何地方的可以证实转基因植物有害的案例。因此,让人很难理解为何在某些地区一直存在坚决抵制转基因作物种植的现象。鉴于转基因作物与生物多样性之间的关系,许多人的第一反应可能是农业本身就是生物多样性最主要的敌人,因为在过去的 1.2 万年中,全球人口数量从最初的 100 万增长到了目前的 72 亿,而农业耕地面积已达到了地球地表土地约 1/3。一般来说,在耕地上进行的农业生产效率越高,产量越高,可持续性则越强,生物多样性受到的危害则越小。在近缘物种间自然发生的杂交是植物进化过程中的突出特征,由于人类选育具有某一改良特性的作物,杂交使得具有目标特性的作物得以富集。这一过程也影响了许多半野生的、似杂草的近缘种的遗传特性,并且在某些特例中,反而使得他们更加类似杂草。转基因既不会加强也不会延缓这些现象,但是它应当作为个案进行研究并解决。

关键词　转基因技术;转基因作物;生物多样性

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能参与到讨论转基因植物在农业中的作用是一件很荣幸的事情。全球农业中转基因作物的比重日益增多,但是这一特殊形式的植物育种为这个高速发展而又饥饿的世界在农作物增产方面所带来的期望远远超过我们目前的认知。在这里,我们将讨论目前已取得的成果、可能存在的问题以及未来的前景。(这篇综述本质上是文献[1-2]的更新,在那 2 篇综述中,我书写了当时我对这个领域的观点和看法。)

作为背景知识,我们必须认识到以下几点:基因的横向转移在自然界是普遍存在的;在对生物体成功进行转基因操作 1 年后,也就是 30 年前,各种深思熟虑的讨论均表明这种生物体的安全性没有一般性的问题;数以亿计的人和数十亿计的家畜食用来源于转基因生物体的食物将近 20 年,但是却没有一个疾病、异常或者其他问题的案例与转基因制品的食用有关。此外,几乎全世界生产的所有啤酒和奶酪以及我们使用的很大比例的药物均有利用转基因生物体合成的产物,但是却没有登记在册的反对声。治疗埃博拉病毒用的试验药物以及唯一可将全球柑橘产业从黄龙病中挽救回来的策略都涉及到转基因生物体的应用。世界上每个国家科学院在对同行评审的证据和大量科学文献全面研究后均已推断这些方法是不存在内在问题的。基于这些事实,我认为那些仍然坚持认为转基因存在一些潜在问题的人要么缺乏对科学的基本理解,要么是因为某些原因而完全不想去接受科学的发现和结论。

根据国际农业生物技术应用服务组织[3]的数据,2013 年有 27 个国家的 1 800 万农民种植转基因作物,种植面积达到 1.75 亿 hm^2。尽管这些转基因作物得以快速应用,一些人仍坚持断言它们有一些未知的、潜在的危险,企图阻碍转基因作物的应用。事实上,也没有任何客观原因使得中国或者其他国家在转基因技术上的开发和使用上选择落后,与此同时,其竞争对手在这一领域快速稳步前进。如果违反科学结论和无视过去 20 年的实践经验,除了造

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成严重的经济损失并同时增加缓解营养不良及解决饥饿问题的难度之外，不会有任何益处。举例来说，中国的环境问题广泛存在[4]，任何延缓采用现代科学项目的举措都将使这个国家的环境更加脆弱，同时增加更多的问题，并且令局部地区的贫困问题更加难以解决。

在我们对于世界粮食形势的综述中，Perry Gustafson、Norman Borlaug 和我[5]列出了 7 种常规改良作物遗传特性的方法，这 7 种方法分别是:组织培养、花药培养、诱变剂技术、分子标记辅助选择的利用、基因组选择的应用、全基因组测序以及可绕过有性生殖过程的植物转化技术。这 7 种最新的方法均可以产生高产作物。令人匪夷所思的是，一些人坚持认为其中某一种方法产生的作物是很危险并且应该避免，但是对同一情景下的其他几种方法却绝口不提!

1　作物的驯化

1.2 万年前，耕作农业由我们的祖先发展起来，往此前溯 200 万年，整个世界人口才仅仅 100 万。农业出现之前，人们通常是 20 至 40 人一起群居生活，他们都是采猎者，必须通过不停地搜寻食物并且立即吃掉来维持生命。早期农民不断地选择和播种繁殖能力强或者高大强壮的植株种子来改良这些植物的特性，用来获得容易收获的植株和在他们生活的地方长势良好的植株。当农民从这些作物中获得大部分食物之后，他们将盈余的食物储存起来以度过艰难的时节。因此，人们可以更大规模地聚集在村庄、小镇或者城市生活。个人可以选择在人口密集的中心地区从事更加专业化的工作，这种分工发展出了许多特色文明。5 000 多年前，书写让人类发展的进程更加快速，书写可以保证事件和发现被准确地记录下来，这样人们就可以不断传阅、讨论并用于将来的实践。

农业耕地在地球上不断扩张，使得人口数目已增长到了 72 亿，但是全球每天仍以 25 万人的速度不断增长，不幸的是，目前仍没有确凿的证据表明在下个世纪人口的增长速度会有所减缓。目前有将近 10 亿人口处于营养失衡状态，这一庞大比例显然会给我们带来许多难题。由营养失衡导致的身心发育不正常，使得这些人难以成为可以正常生活的人。同时又有将近 1 亿人饱受饥饿致死的困扰。考虑到我们目前已经使用全球可承受的生产能力估计值的 156%，该比例还在增长，而我们的人口和消费需求均在不断地膨胀，因此想要显著地改善这一状况将是非常困难的。

2　转基因作物会导致生态破坏吗?

转基因作物的耕种有多大可能性会导致生态破坏，这种破坏的本质又是什么呢?这些问题是我们必须弄清楚的。为了弄清楚这些关系，我们首先应该明白，农业本身可能是过去一直存在并延续至今的对生物多样性最具破坏性的人类活动。人类用来生产粮食的面积在过去 1.2 万年内从 0 到如今覆盖全球约 1/3 的陆地面积。很显然，伴随着草地、森林以及其他自然植被在如此短的时间内转变成耕地，必然导致成千上万的不同物种灭绝殆尽，其中大多数物种甚至还不为人知就已灭绝。在现代农业中，我们通过限制杂草和虫害以保持土壤肥力来达到最大的产量。当然，我们需要尽可能有效、高产地使用我们的耕地，这样我们就不会试图扩张到周围那些低产的土地。这样做也必然导致这些区域生物多样性遭到更为严重的破坏，而且地球上适宜耕种或放牧的土地大都已经被人类所利用。由于这些因素的限制，以及人口数目增长过快，人类对粮食的需求不断增加，更多富裕国家的出现需要更多的肉类和鱼类，粮食产量的增长明显赶不上人口数目的增加。据估计，到 21 世纪中叶，必须增加目前粮食产量的 50%才能养活这个世界不断增长的人口，要实现这一目标我们必须提高现有耕地的生产力。

关于作物的驯化，我们必须强调以下几点。当野生植物被人类栽培种植，这些植物的遗传多样性就开始减少。随着 2 个世纪以前科学耕作和遗传性状的精确测量的出现，作物遗传同质性加强，改良的步伐大大加快。在此基础上，随着 20 世纪 30 年代杂交玉米的开发，耕种面积随之大增。在此背景下，农民会自然而然地选择种植已被证明比他们之前种植的品种更高产的转基因作物或者通过其他手段改良的作物。断言转基因品种的种植会导致土地更加遗传同质化明显是毫无根据的:自从第 1 个转基因作物得以培育种植以来这一过程就一直在进行中，不同之处在于我们现在可以更好地、更有效地控制这一过程。事实上，转基因方法的应用有时会直接保护作物遗传多样性。当我们种植数百种遗传背景

不同的作物，例如种植美国大豆，都可以获得每个品种转基因作物的遗传多样性，因此，转基因方法应用于作物改良对于作物的遗传多样性是没有影响的。

3 两类生物多样性：农业生物多样性(农作物多样性)

讨论种植转基因作物对生物多样性的影响通常使人混淆特定作物和他们的近缘种的遗传多样性和生物多样性残存的关系。前面我已经指出，自栽培伊始，作物的遗传多样性一直在减少。同时，农民也在努力地、有意识地选育一致的、高产的作物，这一选育过程通过选择特定性状来实现，如抗旱、抗虫或抗病；具有较大和较多的种子、果实、叶片或者其他被人类收获后可利用的部位。这些对于作物遗传多样性保留所进行的努力也具有重大意义。尤其是在20世纪20年代至30年代俄国科学家N. I. Vavilov做出重要的基础性研究之后，人们同时将注意力转向了野生亲缘种，以保持遗传多样性。作物起源的中心地带保留着栽培作物与它的近缘种种间变异。这些中心地带有玉米起源的墨西哥南部、诞生向日葵的美国西部平原、产生大豆的热带到亚热带的东亚。水稻的野生近缘种仅局部存在于印度到中国的部分地区。

改良的作物品种均是在最初产生此作物品种的地区培育种植的。自从人们开始栽培植物，基因流回野生或者似草的近缘种中已成为农业的不变特征。以Edgar Anderson为开端，许多学者揭示了不同属和种之间的杂交在许多植物的进化中一直扮演重要角色。从植物进化的这一特征来看，作物与其野生或者似杂草的近缘物种之间的杂交是不足为奇的，这提高了这些作物的遗传变异性并有助于一系列目标性状的选择。比如六倍体(2n＝42)面包小麦(*Triticum aestivum*)的起源，杂交后有一个多倍体化过程，这样就可以保证杂交种及其性状的稳定性，并作为后续混合种植的选择目标。在另一个例子中，玉米起源于大约8 000年前的野生杂草——大刍草，是对其部分农艺性状进行选择改良的过程。目前没有自然存在的植物与面包小麦或者玉米类似，当然面包小麦仅可以与其他六倍体面包小麦杂交形成可育杂交种。相反，玉米可以与具有相同染色体数目(2n＝20)的大刍草杂交，野生的和培育出的植物各自具有的性状均可以在作物和他们的野生亲缘种中以不同的方式进行重组。墨西哥及其他地方玉米的当地品种、农家种的多样性与前述伴随着杂交所得到的重组性状有很大关系。在一个多世纪以前，当杂种玉米和其他改良品种被引入墨西哥之后，这些新品种的遗传性状与当地已存在的“农家种”进行组合。即便在这些品种引入之前，这些农家种也由于农民不断选择栽培它们和其他地方的玉米新品种的引入而不断改变。将农家种认为是一个很多年都固定不变的品种是不合理的，而应该更准确地将它们看作是类似于万花筒中不断变化的颜色，是人们会根据自己的偏好与所得资源进行品种改良的结果。

以上2个例子几乎与其他所有栽培作物在起源及随后的改良过程中均有类似之处。因此，转基因作物与其他作物进化过程中发生的杂交具有相同的方式、相同程度[6-7]，这一点是丝毫不足为奇的。但是，需要强调的是，从基因在同一物种的栽培种和野生种之间的扩散或可能对他们的栖息地产生的影响上来看，转基因是否发生，对这些多样性并没有影响，可能会有影响的是，杂交可能导致某些特定的基因会发生作用并且一些新基因在新的环境中出现适应性问题。

4 基因转移在作物和自然界中如何进行？

由于这两者已经广泛讨论，现在我们将注意力转向基因转移，来看看在栽培种和它们的野生及似草的近缘种群体中有哪些特殊表现。目前广泛使用的转基因产品主要是抗虫的Bt转基因作物、抗草甘膦除草剂的作物以及抗病毒作物。尽管这些基因在本质上是不同的，但是我们可以从这几个例子来窥视整体情况。我们首先会问，如果这些基因存在于野生种或似草的近缘种中会产生什么样的结果。如果似草或者野生植物从害虫中获得了Bt抗虫特性并且这些害虫在这一特定环境中产生了明显的选择压力，那么这些基因可能会存留在似草的物种或似草的群体中。如果它们真被保留了下来，那么植物将会得到更好的保护不被害虫侵食。Snow等[8]和Poppy和Wilkison[9 已经分析Bt基因从向日葵栽培种转移到野生种的具体实例了。他们发现含有Bt基因的野生植株比不含Bt基因的同种野生植株更不易被虫食且具有更强的繁殖力。这一基因转移

过程使得栽培种的田块有更多的野生杂草，但是其他农艺操作可以除去这些转基因杂草。

除草剂耐受的问题就更复杂。不论何时使用除草剂，目标物种或其他物种由于经常暴露于除草剂之下，最终总会产生抗性品种。例如，广泛使用的草甘膦除草剂就导致了不同地区尤其是美国，一些抗性杂草品种的出现。这是使用除草剂(或者农药)必然会出现的问题，原则上是与转基因作物没有任何关系的，只与除草剂如何使用有关。与人类或其他动物解决抗生素抗性一样，已有多种策略被用于处理对除草剂有抗性的杂草；不论是否涉及转基因植物，这些策略将会一直在农业生产中发挥作用。在常绿草的例子中，尽管大多数基因扩散仅限 2 km 的范围，但是草甘膦抗性品种在距离转基因植株种植地 21 km 的地方出现了[10]。由于草甘膦是控制某种草皮中杂草生长的主要方式(该种草皮引自欧洲，并在在森林和公园的空地中广泛种植)，这就成了一个不得不考虑的问题。这一例子也证明了花粉散播的方式对转基因作物或其他栽培作物与他们的野生近缘种分隔种植具有很大的影响。虽然换一种除草剂可以对付这类侵袭，但是种植抗草甘膦除草剂草皮的优势和劣势需要考虑整体环境中它们本身的优点。

以上实例说明了伴随目前广泛使用的基因转移而产生的各种情况以及特定基因转移到作物中与他们在自然中特定情况下的适应性并没有任何关系。由于额外的基因被引入各种作物中，如果这些基因被转移到野生近缘物种中，那么不管这些基因是以何种方式转移到基因组中的，都必须评估这些基因可能的效应。除草剂抗性可以直接从一种作物扩散到与之种在一起的杂草中是毋庸置疑的，但是除草剂的滥用会更直接地导致同样的结果。显然，即便转基因性状不参与其中，每一种情形都必须用正确的农艺实践来解决。

5　作物遗传多样性的保护

为了保护现存于作物以及栽培植物和它们野生近缘种中的基因，我们应该做些什么呢？目前已了解到这些基因可能在未来急剧变化的世界对作物性状的改良具有重要意义。对于农家种以及更古老的栽培品种，期望农民来栽培古老品种是不大可能的，因为这些古老品种产量低，而且与新品种或他们在古老品种与附近引入的品种进行杂交后代中选育出的品种相比，古老品种均不是理想选择。理论上，我们可以资助农民来保持这些传统品种的种植，但是实际上却并没有任何此类实际行动。最有效的保护遗传多样性的方法可能是保留代表遗传多样性的、某一给定物种的所有栽培种、杂草和野生植物的种子。位于墨西哥中部的非常重要的农业组织——国际玉米与小麦改良中心已经对玉米的种质资源进行了搜集。此外，我们可以尝试在他们自然生长的地方保护野生种和这一作物的相关物种。总之，那些被转入用来改良作物特性基因的转基因作物在作物和他们的野生近缘种中的转移对这种作物和他们的近缘种生物多样性的幸存并不构成挑战，并且实际上还有可能促进了遗传多样性的保留。

6　生物多样性总体概括

第二种具有讨论和分析价值的生物多样性类型则是总体上的生物多样性了。据估计，地球上目前有 1 200 万种原核生物和数百万种细菌和古细菌，这些生物体是地球上生命的基础。这些生物体数十亿年的生命活动不仅改变了土地、水和大气的特性，还使得他们生存了下来并支撑起我们的生命。植物则直接或间接地为我们提供粮食以及大部分的医药；作为一个整体的生态系统维持了我们赖以生存的土地和水；那些美丽、多样的生物体则极大地丰富了我们的精神世界。人类未来的发展很大一部分需要依赖于我们维持生物多样性以及可持续地利用生物体特性的能力。由于这些原因，转基因作物的栽种是否会威胁到生物整体多样性是至关重要的。我们知道物种会很快灭绝的许多原因。其中一个就是由于农业、城市扩张、林业或者其他原因所导致的自然栖息地的严重破坏；还有就是物种入侵以及全球气候变化等原因。全球气候变化正日趋加快，据政府间气候变化委员会(IPCC)最近发布的报告估计，截至本世纪末，气候变化将导致约 1/5 或更多物种的灭绝。这些因素共同作用的结果就是，地球上超过一半的物种将在本世纪末到来前灭绝，其中绝大多数物种在灭绝前我们都未能有所了解。现有生物体如此大比例的灭绝将导致我们重建全球可持续发展的能力面临重大损失；显然，在减缓目前和将来的共同利益损失方面我们有一致的诉求。

转基因作物的种植和生物体的灭绝之间会有什

么关系呢？我们已注意到，农业本身就会导致严重的生物灭绝，低层次农业相比于密集的、高产的农业对生物灭绝的危害更大，因为它覆盖的面积更大、影响的物种更多。传统农业的重点是排除那些在富饶的土地上生存的动植物，选择优良品种保持下来，它的成功往往是以在多大程度上成功排除一些动植物来衡量的。将传粉昆虫或其他有益生物体生存的栖息地保留下来对人类来说显然是有益的，但是土地本身则大体上应尽可能地摆脱生物多样性。在转基因作物的例子中，降低或消除对农药应用的需求，附近的生物群体由于不会受到化学药品的伤害，也将获益良多。我之前已经提及，更高产的、密集的农业更有可能保护生物多样性。一般来说，栽种转基因作物和生物多样性的幸存是正相关的关系，为什么《生物多样性公约》在转基因作物种植以及在不同国家之间运移如此畏首畏尾，这对我来说仍然是一个谜。

7 转基因作物对非目标物种的影响

仅根据转基因作物种植田块之外物种受到影响的几个特例，就声称Bt毒蛋白转基因作物可能对其他并非目标生物产生影响是不对的。同样的情况也发生在除草剂农达(Roundup)的抗性上，这种情况下，可以利用对特定除草剂有抗性的转基因作物来除掉耕地上的杂草。如果除草剂从田间扩散出去，对生态系统的真正破坏将不可避免；但是如果它们真能提高产量，那么这将对其周边地区生物多样性的幸存是有利的。如果除草剂或者农药随意在农田之外或其他地方滥用，那么必然会引起问题。另一方面，如果能够像欧洲那样有效地控制农药的使用，那么对生物多样性和人类健康的主要负面影响就可以避免。

8 基因从转基因作物转移到同一物种的非转基因作物中

这个问题本质上是我们人类自己引起的。它在很大程度上是由于美国农业部不合理地将转基因作物归为“非有机”导致的，这反过来又催生了对其是否“纯净”的担忧，这一概念对植物如何演化以及作物遗传特性如何通过多种方式进行改变给出了非常奇怪的见解。这一理念或者见解丝毫没有一点理性的基础，反而会在可持续农业的发展道路上增加额外的障碍；我尤其认可M. S. Swaminathan所给出的建议，他认为这2种方法可以携手促进作物优良性状的改良。就像我之前强调的那样，农业本身就不是自然状态；所有的栽培作物和驯化的动物都是经过多年遗传操作改良之后产生的。在全球急需增加粮食产量的大背景下，如果仅仅以它们具有潜在威胁为理由，在这种意识形态下排斥特定的作物育种的方法是极其不明智的。不论某一作物的花粉是否如胡桃、白杨、松树或草一样通过风来传播，花粉都有可能传播很远的距离，导致某些性状在离它原来位置很远的地方表现出来。对于许多其他作物，比如苹果、马铃薯、油菜、南瓜、苜蓿、莴苣、向日葵、果树和浆果作物，他们的花粉是由昆虫传播的，这些作物花粉传播的距离则取决于那些传粉昆虫的习性、数量和习惯以及他们所接触的花的特性了。一些作物，比如水稻、小麦、大麦和大豆，则是自花授粉，他们的花粉只有极少的一部分可以通过风扩散出去。这些基因是否会像通常一样在新环境下存留下来往往取决于那些接受这些外来花粉的植株所在环境的选择压力。通常，如果不考虑特殊情况下发生的基因转移的话，没有任何理由担心这些花粉扩散可能引起一些问题。

9 新品种杂草产生的可能性

目前共有2万多种植物被认为是杂草，平均每20个物种中就有1个是杂草。这些杂草广泛分布在世界各地的自然或人工环境中。有些甚至生长在作物之间，这种类型的杂草往往对作物产量有负面影响。大多数杂草是伴随着农业或园艺被人类从一个地方引入另一个地方的。有些杂草则是由于偶然地污染或粘附在一些产品或物品上被运输到其他地方去的。抵制转基因作物的观点之一即是使用转基因会导致新的、极具侵略性的杂草的产生。事实上，有些非常重要的杂草，如约翰逊草和红色杂草稻(栽培水稻和野生水稻杂交产生)，就与农作物有关。这些杂草往往为农业生产带来麻烦，因为他们都有一些与起源作物类似的特性，因此很难得到控制。然而，这些例子都与转基因技术无关；并且没有例子表明：相比其他杂草，我们应该对这些假定的杂草更加畏惧。

不可否认的是，对害虫及除草剂有抗性的基因从作物转移到特定杂草确实会增加在农田中控制这

些杂草的难度。因此，对食用甜菜而言，获得除草剂抗性的野生甜菜就是一个大麻烦。目前人们已知道若干此类的例子了，前文讨论提到的向日葵就是一个。但是，我们应该在数千个已知的极具侵略性的杂草的大背景下考虑这个问题并且应该秉承具体问题具体分析的态度。有些人认为，杂草的特性与大多数栽培植物是截然不同的，许多作物在自然界中不能自己繁殖——玉米和大豆就是最好的明证，因此认为它们促进新种杂草的形成是不太可能的。

10　法　律

20 世纪 80 年代，我参与了《生物多样性公约》的制定，对当前斤斤计较转基因作物这一事实我感到非常难过。其所谓的生物安全准则并不是基于任何有根据的科学原理，是以《卡塔赫纳生物安全议定书》或其他形式向某些人授权，而这些人出于个人原因——可能是政治性的原因——希望减缓我们用来生产这个世界急需粮食的工具的付诸使用。伴随监管转基因作物而来的是不明智、无意义的争论，这已经消耗了数百位外交官和理想主义者的精力，但对保护世界生物多样性没有产生丝毫作用，而保护世界生物多样性正是我们希望在生物多样性公约下能得到的结果。就像我在这些评论中解释的那样，目前没有明确的科学基础来假定与转基因生物相关的生物安全原则会对全球范围内饱受威胁的生物多样性幸存起到任何作用。从这一角度来说，《生物安全议定书》明显正在向其设定初衷靠拢——即保护生物多样性，这对我来说是一件值得高兴的事，因为保护生物多样性也是我为之奉献一生的事业。

11　结　论

1.2 万年前农业的出现就一直是生物多样性的主要敌人。在人口数目由 100 万增加到现在的 70 多亿的过程中，尽管我们已经在大量土地上密集地种植了许多作物，但是仍有约 10 亿人处于营养不良的状态。目前，人口数目已经超过了这个星球承载能力的 50％，我们还在以不断增长的速度消耗着这个星球的资源。而一些组织和个人置这些重要的事实于不顾，用毫无科学支持的观点，去抵制可以对作物进行改良进而提高产量并使得人类能够持续发展的方法。对任何国家而言，基于政治原因对这一技术不闻不问都是一个可耻的错误。

在任何情况下，自然系统中广泛分布的进行必要耕作的低等级农业生产，对生物多样性的破坏远超过在特定区域集中的、大规模的农业生产。与之相反的是，一些无转基因作物的耕作系统——尤其是大量使用化学药品的欧洲，对环境的破坏更为巨大。我认为，由于非科学的原因而拒绝接受转基因作物，并使数十亿人承受多种伤害，这是非常不道德的。

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Global perspective: GM crops and biodiversity

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Abstract More than 30 years after the development and testing of transgenic techniques that mimicked the horizontal transfer of genes that is widespread in nature, these techniques were being used to produce a wide variety of medicines, virtually all beer and cheese consumed in the world, and were planted (in 2013) by approximately 18 million farmers on 175 million hectares in 27 countries. Hundreds of millions of people and billions of farm animals have been consuming these plants and products derived from them for nearly 20 years without a single verified case of harm encountered anywhere. Against this background, it is difficult to understand the resistance to cultivating such crops that persists in some regions. Concerning the relationship between GM crops and biodiversity, one may first note that agriculture itself is a major enemy of biodiversity, having spread to occupy about a third of the world's land surface over the past 12 000 years as the human population has grown from an initial 1 million people to more than 7.2 billion at present. The more efficiently agriculture is carried out on cultivated lands and the more productive and sustainable it is there, the less harm to biodiversity generally. Naturally-occurring hybridization between related species is a prominent feature of plant evolution, and has resulted in the genetic enrichment of crops as human beings have selected them for improved characteristics. It has also affected the genetic characteristics of the wild and weedy relatives of many crops, and in a few cases increased their weediness. These phenomena are neither enhanced nor retarded when transgenes are involved, but should be studied and dealt with agronomically on a case-by-case basis.

Key words transgenic techniques; GM crops; biodiversity

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1 Introduction

It is a pleasure to participate in this discussion of the role of GM plants in agriculture, now and in the future. The proportion of world agriculture devoted to such crops increases every year, but the promise that this particular form of plant breeding offers for increasing crop productivity in a rapidly-changing and hungry world is much greater than those we have realized so far. We are here to discuss present accomplishments, possible problems, and future promise. (The present review is essentially an updating of Raven papers[1-2] in which I covered the state of thinking about this area as of that date.)

As background, we may note that horizontal gene transfer is common in nature; that in the first years after the successful application of transgenic methods for organisms, thirty years ago, thoughtful discussions revealed no generic problems concerning the safety of such organisms; and that nearly twenty years of consumption of foods from GM organisms by hundreds of millions of human beings and billions of farm animals have led to the detection of not a single case of sickness, abnormality, or other problem associated with their use. In addition, virtually all beer and cheese manufactured anywhere in the world and a large proportion of our medicines involve products synthesized by transgenic organisms, with no objections registered. The trial medicines for the Ebola virus, as well as the only practical strategy for saving the global citrus industry from Huang Long Bing disease involve transgenic organisms too. Every national academy of sciences in the world has concluded on the basis of peer-reviewed evidence and comprehensive studies of the scientific literature that there is no intrinsic problem with these methods. Based on these facts and relationships, I conclude that those who continue to insist that there is some underlying problem with such methods either lack an understanding of science or for some reason don't care to accept scientific findings and conclusions.

According to the ISAAA[3] GM crops were planted in a record 175.2 million hectares by 18 million farmers in 27 countries in 2013. Despite the rapid adoption of such crops, some continue to assert that they pose some mysterious unknown, intrinsic danger that should preclude their use. In fact, there is no objective reason that China or any other nation should choose to be left

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behind in the use or further development of this area of technology while their economic rivals forge rapidly ahead. There is nothing gain but serious economic loss and increased difficulty in alleviating malnutrition and starvation by continuing to act contrary to the findings of science and the practical experience of the past two decades. For example, China's environmental problems are extensive[4], and any delay in adopting contemporary scientific programs will weaken the nation, increase the problems, and make regional poverty more difficult to conquer than it would be otherwise.

In our review of the world food situation, Perry Gustafson, Norman Borlaug, and I[5] listed seven contemporary methods that are used regularly to improve the genetic characteristics of crop plants: tissue culture, anther culture, mutagen technology, the utilization of marker-assisted selection, the application of genome-wide selection, whole genome sequencing, and plant transformation technology to produce GMOs while by passing the sexual process. These seven are but the latest ways to produce more productive crops designed to flourish in our rapidly-changing world. It seems bizarre that some chose to argue that the crops resulting from one of these methods as dangerous and to be avoided, whereas the others are never mentioned in this context!

2 The domestication of crops

Crop agriculture was developed by our ancestors about 12 000 years ago, when, after a history that extended back more than 2 million years, there were still only about 1 million human beings in the entire world. Pre-agriculturists secured their living as hunter-gatherers, living in bands of usually about 20-40 people, continually searching for food and necessarily eating it soon after finding it. Early agriculturists would have improved the characteristics of their crops continuously by selecting and sowing seeds from the more fertile or larger individuals, those that were easier to harvest, and those that grew well in the places where the farmers lived. When these farmers succeeded in obtaining a major portion of their food from their crops, enough of the surplus could be stored to provide food for them during unfavorable seasons. As a result, it became possible for people to live together in increasing numbers in villages, towns, and eventually cities. Individuals could choose to follow specialized careers in such centers, this specialization gradually leading to the development of most features of what we recognize as civilization. Human progress was spurred on by the invention of writing about 5 000 years ago, a development that allows facts and discoveries to be recorded accurately for review, comment, and future use.

As agricultural lands spread gradually over the earth, our numbers have climbed to 7.2 billion people, a number that is continuing to increase by about 250 000 people net every day. Unfortunately, there is no firm evidence that the growth of our numbers will slow even in the next century. This obviously poses a problem of enormous proportions, since about 1 billion of us are malnourished currently. The minds and bodies of the people who are malnourished fail to develop properly, and these individuals never become fully functional human beings. At the same time, about 100 million people are in imminent danger of starving to death. Significantly improving this situation will be very difficult in view of the fact that weare already using an estimated 156% of the world's sustainable productivity, the proportion growing every year (http://www.ootprintnetwork.org) as our numbers and our demands for increased consumption continue to swell.

3 Ecological damage from GM crops?

How likely is it that ecological damage will result from the cultivation of transgenic crops, and what would the nature of such damage be? In order to understand these relationships, we first must understand clearly that agriculture itself is perhaps the single human activity that has been and remains the one most destructive to biodiversity. The area that human beings devote to food production has grown from none to about a third of the world's land surface over the past 12 000 years!It is clear that the accompanying conversion of grasslands, forests, and other types of natural vegetation over such a short period must have resulted in the extinction of tens or hundreds of thousands of species of organisms, most of them never recognized before they disappeared. In modern agriculture, we seek to limit the occurrence of weeds and pests in our fields, to conserve soil fertility, and to achieve maximum productivity. Certainly we need to use our agricultural lands as efficiently and productively as possible, so that we will not attempt to expand their extent widely into surrounding, less productive lands. Doing so will increase greatly to the damage to biodiversity in a given region. Most of the world's land that can usefully be cultivated or grazed is already occupied. Within these limits, food production is growing more slowly than our constantly increasing human population, with demands for more food and especially for more meat and fish, environmentally very expensive to produce, rising rapidly in the world's more affluent countries. It is estimated that we must produce an estimated 50 percent more food than we do now by mid-century to feed the world's growing population, a goal that we can achieve largely by increasing productivity on the lands we are already cultivating.

About the domestication of crops, we may say the following. As soon as wild plants were brought into cultivation, the genetic diversity of those plants began to decrease. With the advent of scientific agriculture and accurate measurements of inherited characteristics about two centuries ago, the pace of crop improvement accelerated as the genetic homogeneity of cultivated fields became greater. Following major advances, such as the development of hybrid maize in the 1930s, the size of cultivated fields in many regions has increased. Against this background, it should come as no surprise that farmers would choose to grow transgenic (GE) or otherwise improved strains of crops in these large fields if such strains proved to be more productive than the ones they had grown earlier. To assert that the use of GE strains somehow made the fields more homogenous genetically, however, is patent nonsense: that process has been underway since the time when the first crops were cultivated, the difference being that we can pursue it better and more efficiently at present than we could formerly. In fact, the application of transgenic methods sometimes actually leads directly to the preservation of crop genetic diversity. Where hundreds of genetically distinct strains of crops are grown, as for example in the cultivation of soybeans in the United States, GE versions of all of the individual strains have been made available. The overall genetic diversity in the fields remains as high as it was before transgenic methods were applied to improving the crop.

4 Two kinds of biodiversity:agro-biodiversity (crop diversity)

Discussions of the effects of cultivating GE crops on biodiversity often confuse the genetic diversity of particular kinds of crops and their relatives with the survival of biodiversity in general. As I pointed out earlier, the genetic diversity of crops has decreased steadily ever since plants were first brought into cultivation. At the same time, farmers have made a conscious effort to develop crops with uniformly high productivity, based on such features as drought resistance; pest or disease resistance; and larger and more abundant seeds, fruits, leaves, or whatever parts of the plant were ultimately harvested for use, efforts in which the genetic diversity remaining in the crops has been important. Especially since the fundamentally important studies of the Russian scientist N. I. Vavilov in the 1920s and 1930s, attention has also focused on the wild relatives of cultivated plants as important reservoirs of genetic diversity. The centers of origin of crops began to be seen as places where a high degree of variability often persists in the crop species and its relatives. Examples of such centers would be southern Mexico for maize, the Western Plains of the United States for sunflowers, and temperate to subtropical eastern Asia for soybeans. The wild relatives of rice persist, but very locally, from India to China.

Improved crop varieties are cultivated in all of the areas in which the individual kinds of crops were originally derived. And gene flow to wild or weedy relatives of crops has been a constant feature of agriculture ever since people began to cultivate plants. As many authors, starting especially with Edgar Anderson, have documented, hybridization between distinct races and species has played and continues to play a major evolutionary role for many groups of plants. In view of this characteristic of plant evolution in general, it should not be surprising that hybridization between crops and their wild and weedy relatives is important in enhancing the genetic variability of both the crops, facilitating the selection of suites of desired characteristics, and of their weedy or wild relatives. In some cases, as for example in the origin of hexaploid ($2n=42$) bread wheat (*Triticum aestivum*), the hybridization has been followed by polyploidy, stabilizing the hybrid and its characteristics as an object for further selection through selective planting in the mixed fields. In another example, maize (*Zea mays*) originated about 8 000 years ago with the selection of plants with improved agronomic characteristics from teosintes, wild grasses that occurred in the region. There are no naturally-occurring plants that resemble either bread wheat or maize, and of course bread wheat can form fertile hybrids only with other hexaploids. Maize, by contrast, can hybridize with teosintes that have the same chromosome number ($2n=20$) and the characteristics of the wild and cultivated plants can be recombined in different ways both in the crops and in their wild relatives. The diversity of local strains, land races, of maize in Mexico and elsewhere has a great deal to do with the recombination of these features following hybridization of the sort discussed.

When hybrid maize and other improved varieties were introduced into Mexico starting more than a century ago, the genetic traits of these new strains were combined with those of the existing "land races". Even before these introductions, the "land races" were changing continuously because of selection by the farmers cultivating them and the introduction of new races of maize from elsewhere. It is unreasonable to regard the "land races" as fixed strains that have persisted for all time, but more accurate to view them as we do the colors seen in a Kaleidoscope, shifting continuously and being improved according to the preferences of the people growing them and the genetic resources available to them.

The two examples just reviewed have parallels in the origin and subsequent improvement of virtually all cultivated crops; therefore, it should not be surprising that GE crops hybridize in the same way and to the same degree as takes place in the evolution of all other crops hexaploid[6-7]. It needs to be stressed that whether transgenes are involved has no bearing on the spread of genes between cultivated and wild plants of the same species, or on the likelihood that they may present special problems in the habitats where they occur. The only points that matter concern the nature of particular genes and their adaptive value in the new genetic context that they may reach as a result of hybridization.

5 How do transgenes behave in crops and in nature?

Since they are widely discussed, we now turn our attention to transgenes to see what special behavior they may have in populations of crops and their wild and weedy relatives. The principal transgenes that are in widespread use at present include especially Bt protection from pests; glyphosate-ready crops; and virus resistance. Although genes obviously differently in natural situations, we may use these as examples of the whole. Therefore, we might first ask what the consequences of these genes occurring in wild or weedy relatives might be. If the weeds or wild plants gained Bt protection from their pests, and if the pests generated significant selective pressures in the particular environment, the genes might persist in the wild or weedy populations. If they did persist, the plants would be better protected from the pests that were attacking their cultivated relatives than they would be otherwise. Snow et al.[8] and Poppy and Wilkinson[9] have analyzed a concrete example of such a process, concerning the movement of a Bt transgene from cultivated to wild sunflowers (*Helianthus annuus*). In the wild plants, the Bt gene was demonstrated to reduce herbivory and increase fecundity over the levels observed in wild populations of the same species that lacked the Bt gene. Such a transfer could enhance the weediness of the wild plants in the fields of their cultivated relative, but other agronomic practices could be used to eliminate the transgenic weeds.

The question of herbicide resistance is more complex. Whenever herbicides are used in agriculture, resistant strains of the target species and other species that are regularly exposed to the herbicides will eventually appear. For example, the widespread use of glyphosate has resulted in the appearance of several resistant strains of weeds in different areas, especially in the United States. This is a general property of herbicide (or pesticide) use and in principle has nothing specifically to do with whether GE crops are the ones treated or not, but everything to do with how the herbicides were applied. Various strategies have been employed to deal with herbicide-resistant weeds, similar to the strategies used for dealing with antibiotic resistance in human beings or other animals; and they will continue to be needed in agricultural situations whether or not GE plants are involved. In the case of bentgrass, *Agrostis stolonifera*, glyphosate-resistant strains appeared up to 21 km from the plots where the GE plants were cultivated, although most of the gene flow took place within 2 km[10]. This is considered a problem in the sense that glyphosate is the principal means of controlling this introduced European grass, widely grown as turf but weedy, for example, in clearings in forests and parks. This example also demonstrates the fact that the mode of pollen dispersal greatly affects the effects of growing GE crops, or any cultivated crops, at certain distances from their wild or weedy relatives. Clearly alternative herbicides could be found for such infestations, but the advantages and disadvantages of planting glyphosate resistant turf need to be considered on their own merits in the context of the environmental situation overall.

These examples illustrate some of the diverse situations that can arise with the transgenes that are currently in widespread use and, again, how the particular genes got to the crops has no bearing on their adaptive value in particular situations in nature. As additional genes are introduced in various crops, they should be evaluated for their possible effects if they were transferred into wild or weedy relatives regardless of how the genes were added to the genomes of the respective crops. It is certainly the case that herbicide resistance, for example, could spread directly from a crop to closely related weeds growing with it; but overuse of the herbicide will lead to the same result even more directly. Clearly, every situation must be dealt with by appropriate agronomic practices, as would be the case even if GE traits were not involved.

6 Preserving the genetic diversity of crops

What can be done practically to preserve genes that are still present in the crops and in cultivated plants and their wild or weedy relatives?We recognize that these genes can prove valuable to improve the performance of the crops in the future, especially in our rapidly-changing world. For “land races” and their equivalents, older cultivated strains, it is not reasonable to expect farmers to go on cultivating older strains that are not as productive or not seen by them as being as desirable as the newer ones, or ones they could select from hybrids with newer strains introduced into their vicinity. We could theoretically subsidize the farmers to keep growing traditional strains, but there has been no real activity along these lines. Probably the most effective way to protect the genetic diversity is to conserve seed samples representing the genetic diversity that exists now in seed banks, both for cultivated, weedy, and wild plants of a given crop, as has been done for maize by CIMYT, a vitally important agricultural institution in central Mexico. In addition, we should clearly try to protect the wild strains and species related to the crops in the areas where they grow naturally.

In summary, the movement of transgenes (genes that have been transferred to GE crops to improve their characteristics) among the crop and its wild or weedy relatives appears to pose no challenge for the survival of the biodiversity of the crop and its relatives, and might actually improve the retention of genetic diversity in either situation.

7 Biodiversity overall

The second kind of biodiversity that merits discussion and analysis here is biodiversity in general, the estimated 12 million kinds of prokaryotic organisms and the additional millions of kinds of bacteria and Archaea that form the basis of life on Earth. Not only did the life activities of these organisms over billions of years mold the current characteristics of the soil itself, the waters, and the atmosphere, they continue to maintain them now and to sustain us. Thus plants supply all of our food directly or indirectly and a major proportion of our medicines; ecosystems as a whole maintain the soil and water on which we depend; and the beauty and diversity of organisms nourishes us spiritually. A major portion of human progress in the future will depend on our ability to maintain biodiversity and use the properties of organisms sustainably, often doubtless in ways that we do not yet recognize.

For these reasons, it is of fundamental importance to ask whether the cultivation of transgenic crops may threaten the continued existence of biodiversity generally. We know many of the reasons why species are becoming extinct so rapidly. Among them is the destruction of natural habitats, often for agriculture or because of urban sprawl, forestry, or other reasons; the spread of invasive species, pests, and pathogens; and global climate change. Global climate change is advancing rapidly and according to estimates published in the latest report of the Intergovernmental Panel on Climate Change (IPCC) might itself be responsible for the loss of a fifth or more of all species by the end of this century. As a result of all these factors, more than half of all species on Earth, the great majority of which will be unknown to us at the time of their is appearance, may become extinct by the end of this century. The loss of such a high proportion of the existing organisms would lead to an increasingly significant loss of our ability to rebuild global sustainability; we clearly have a great common interest in slowing down the loss for our common present and future benefit.

What is the relationship between the cultivation of GE crops and biological extinction?As we have already noted, agriculture itself is a powerful driver of biological extinction, and low-grade agriculture much more so than intensive, productive agriculture, because it impacts more species over much wider areas. Agriculture has traditionally been focused on the exclusion of plants and animals other than those being cultivated from the productive fields, and its success has often been judged in part by the degree to which such exclusion has been successful. It is clearly beneficial to maintain habitats among the fields where pollinating insects and other beneficial organisms can persist, but the fields themselves by and large are kept as free from biodiversity as possible. In the case of GE crops that lessen or eliminate the need for pesticide applications to the crops, the neighboring natural communities actually benefit by not receiving substantial amounts of such chemicals on a regular basis. As I have mentioned earlier, the more productive intensive agriculture can be, the greater the chances for preserving biodiversity in the areas not devoted to the cultivation of crops or pasturing animals. In general, it is clear that the relationship between the cultivation GE crops and the survival of biodiversity is a positive one, and it is a mystery to me why the Convention on Biological Diversity has historically put such a premium on restricting the cultivation and movement of such crops between countries.

8 Effects of GE crops on non-target species

To speak of a few particular examples of effects outside of the fields, it has been claimed that those crops that have been modified to produce Bt toxin, a natural toxin from the bacterium *Bacillus thuringiensis*, may have a detrimental effect on other organisms that were not intended as targets. The same is true of Roundup (glyphosate) resistance, where transgenic plants resistant to a particular herbicide are used to eliminate weeds from cultivated fields. If the herbicides are spread outside of the field, real damage to ecosystems may occur; but if they make greater productivity in the fields more likely, that will prove a benefit for the survival of biodiversity in neighboring areas. If the herbicides or pesticides are used deliberately outside of the fields or drift there, there is of course a problem. On the other hand, by avoiding the application at the levels routinely applied, for example, in Europe, that major negative effects both on biodiversity and on human health are avoided.

9 Transfer of genes from a GE crop to non-GE crops of the same kind

The problem here is essentially one that we have created for ourselves. It arises to a large extent because of the irrational classification of GE crops as “non-organic” by the U. S. Department of Agriculture, which in turn drives a concern about their “purity”, a strange notion given the ways in which plants actually evolve and the numerous ways that crop genetics is routinely altered. I can see no rational basis for this designation, which basically puts an additional obstacle in the way of attempts to achieve sustainable agriculture, and I particularly would like to endorse the suggestion made here by M. S. Swaminathan that these two approaches to agriculture be brought together to accelerate the improvement of desirable characteristics of crops. As I emphasized earlier, agriculture itself is unnatural; all cultivated plants and domesticated animals have characteristics that they have acquired over the years as a result of genetic manipulation. In the context of a world that so badly needs increased food production, it seems unwise to rule out particular methods of plant breeding purely on ideological grounds that suppose they pose imaginary threats. Whether the pollen of a particular crop is transported by the wind, as in walnuts, poplars, pines or grasses, the distances the pollen may move may be relatively great and the traits may show up at a great distance from the place where they have been introduced. For many other crops, such as apples, potatoes, canola, squashes, alfalfa, lettuce, sunflower, fruit trees and berry crops, the pollen is transferred by insects and the distances the pollen regularly travels will depend on the nature, abundance and habits of the individual pollinating insects and the characteristics of the flowers they visit. Some crop plants, such as rice, wheat, barley and soybeans, self-pollination is the rule and only a very small proportion of the pollen is shed and dispersed by the wind. Whether the genes persist in their new context, as always, depends on the selective environment to which the plants that have received them are placed. In general, there is no reason that any of the possible outcomes should be a matter of concern regardless of the degree of gene transfer that may occur in particular situations.

10 The possible production of new kinds of weeds

Some 20 000 kinds of plants, about one of each twenty species, are regarded as weeds, spreading in natural or artificial situations somewhere in the world, with those that grow among crops, usually affecting their yield negatively. The great majority of weed species were originally introduced by people from one place to another, often deliberately, and usually in connection with agriculture or horticulture. Other kinds of weeds have moved accidentally, contaminating or adhering to some product or object that is itself transported. One of the arguments used against planting GE crops is that in some way they might give rise to new, particularly aggressive weeds that would otherwise not occur. There are in fact a few examples of the origin of important new weeds involving crops, notably Johnson grass (*Sorghum halepense*) and weedy red rice, which originated as a hybrid between cultivated rice, *Oryza sativa*, and its progenitor species, *O. rufipogon*. Both of these weeds pose serious agronomic problems because they have characteristics similar to those of the crops from which they were derived and thus are particularly difficult to control. Neither of these cases, however, involves GE technology and there are no examples to justify fearing such hypothetical weeds more or less than others.

By contrast, the movement of genes for resistance to pests or herbicides from the crops into particular weeds can certainly add to the difficulty of controlling these weeds in the cultivated fields. Thus, wild beets (*Beta vulgaris*) that have acquired herbicide resistance are important weeds in the fields where a domesticated strain of the same species, the sugar beet, is grown; a modest number of similar examples are known, among them that of sunflowers, discussed earlier. One should, however, view this problem in the context of the thousands of known aggressive weeds and deal with it on a case-by-case basis. As many have pointed out, the characteristics of weeds are very different from those of most cultivated plants, and many crops—maize and soybeans being good examples—never establish themselves in nature and rarely even re-seed in cultivation, so that their possible contribution to the formation of new weeds is particularly difficult to imagine.

11 Legalities

Having been involved personally in the formation of the Convention on Biological Diversity in the 1980s, I am truly saddened by the fact that it has become so preoccupied with GE crops. The so-called principle of “biosafety” is not based on any valid scientific principles, and working it up through the Cartagena Protocol and by other means has given license to those who for personal reasons, presumably of a political nature, wish to slow down the spread of the tools we have available to produce food for a world that so badly needs it. The unwise and wasteful arguments associated with regulating GM crops have consumed thousands of hours of time by hundreds of diplomats and idealists, and not produced any result of the slightest use for the preservation of the world’s biodiversity, which we all hoped would be the outcome of activities under the mantle of CBD. As I have explained in these remarks, there is no valid scientific basis to assume that “biosafety” principles concerning GE organisms would have any effect whatever on the survival of biodiversity, which is so greatly threatened throughout the world. In that sense, it seems to me to be a good thing that the CBD is apparently now moving on to issues connected with the purpose for which it was formed, namely, the preservation of biodiversity—a cause to which I have devoted most of my life.

12 Conclusions

Agriculture has since its invention some 12 000 years ago been a principal enemy of biodiversity. As our numbers have increased from about 1 million then to over 7 billion, we have grown more food more intensively and over larger areas, and still about 1 billion of us remain malnourished. We exceed the sustainable capacity of our planet by more than 50% each year currently, so that in effect we are degrading the resources of our planet progressively and at an ever-increasing rate (http://www.footprintnetwork.org). Despite this profoundly important relationship, certain organizations and people, with no scientific facts on their side, have chosen to oppose one of the many ways in which the genetics and therefore the productivity and sustainability of our crops can be improved. It would be a shameful error for any nation to turn its back on this particular technique for political reasons.

At any event, low-grade agriculture spread out in natural systems, being necessarily practiced over extensive areas, is collectively far more damaging to biodiversity than intensive, large scale agriculture in prescribed areas. In contrast, the environmental damage caused by some GM-free farming systems, especially in Europe, which involve the application of large amounts of chemicals to their crops and expose their people to harm, is enormous. It seems to me to be particularly immoral to adopt the non-scientific reasoning underlying the lack of acceptance of GM crops considering the various kinds of harm done to billions of people as a result of this self-indulgent strategy.

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