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Feasibility of new breeding techniques for organic farming

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Organic farming is based on the concept of working 'with nature' instead of against it; however, compared with conventional farming, organic farming reportedly has lower productivity. Ideally, the goal should be to narrow this yield gap. In this review, we specifically discuss the feasibility of new breeding techniques (NBTs) for rewilding, a process involving the reintroduction of properties from the wild relatives of crops, as a method to close the productivity gap. The most efficient methods of rewilding are based on modern biotechnology techniques, which have yet to be embraced by the organic farming movement. Thus, the question arises of whether the adoption of such methods is feasible, not only from a technological perspective, but also from conceptual, socioeconomic, ethical, and regulatory perspectives.

Organic farming and biotechnology

Although conventional agriculture is highly productive, it is often considered incompatible with the principles of alternative approaches to food production, such as organic farming. Traditional breeding methods have been exceptionally successful in creating crop plants with high yields and other desirable properties, but modern crops often require intensive management to avoid being outcompeted by weeds, infected by diseases, or eaten by insects. Organic farming is an agricultural system that aims to mimic processes in natural ecosystems for the provision of nutrients and pest control, instead of relying on chemical inputs. For this reason, chemical fertilizers, pesticides, and other agents used in conventional agriculture are restricted or prohibited in organic production. As a consequence, productivity is often lower in organic than in conventional agriculture [1–4], and several strategies have been suggested to close this yield gap between high- and low-performing conventional systems [5–7]. A plea for merging organic agriculture and genetic engineering approaches has previously been published [8]. Here, we discuss the feasibility, in a broad sense, of introducing new methods of plant biotechnology to enable the sustainable intensification of organic farming (i.e., increased production from existing cultivated land with minimal pressure on the environment).

Organic farming excludes several practices due to sustainability, health, and safety concerns. These concerns are reflected in the four principles of health, ecology, fairness, and care, as defined by The International Federation of Organic Agriculture Movements (IFOAM) [9]. According to these principles, certain forms of biotechnology have been considered to be irreconcilable with organic agriculture, as stated by IFOAM: 'Organic agriculture should prevent significant risks by adopting appropriate technologies and rejecting unpredictable ones, such as genetic engineering' [9]. However, as technologies evolve, it is not obvious that all forms of technology, especially those involving some kind of genetic modification *sensu lato*, should be deemed incompatible with organic farming. The statement from IFOAM suggests that genetic modification of plants has unpredictable consequences. However, whether, and to what extent, this is so, is a contingent empirical question that must be examined in detail for any crop developed. Moreover, the issue is complicated further by the fact that the term 'genetic engineering' spans several strategies in modern plant biotechnology that cannot adequately be evaluated as one. For instance, reverse breeding (rewilding) aims to bring crops 'back to nature' by furnishing them with lost properties that their ancestors once had. The most direct and predictable tools for (re)developing crops

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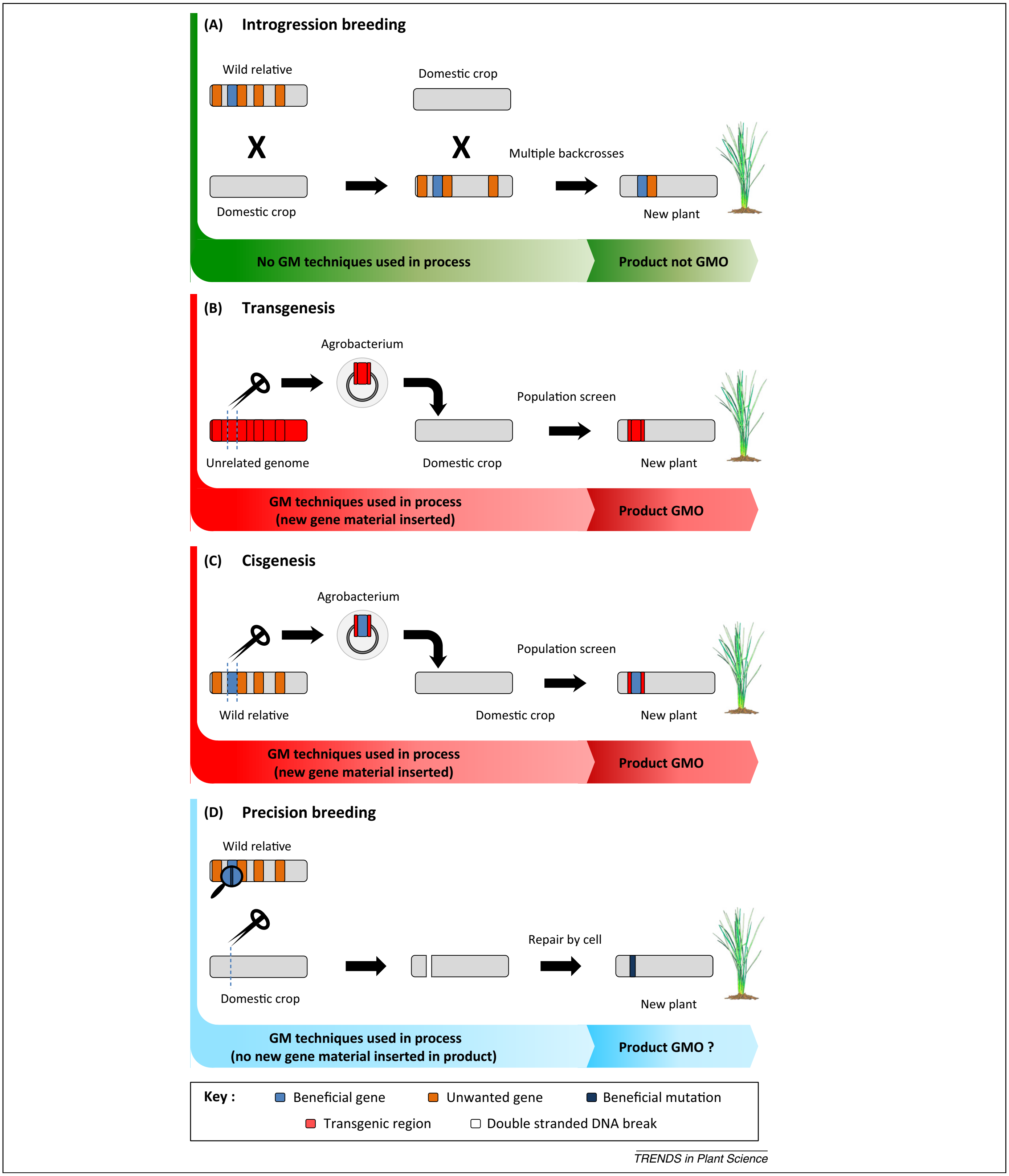

Figure 1. Breeding techniques available for rewilding of crop plants and their legal feasibilities in the European Union (EU). **(A)** Introgression breeding is the standard method used to introduce genes and traits from wild plants into domesticated crops. This method uses an initial cross between the crop and the wild relative of interest followed by repeated backcrossing to the domesticated crop to erase as much genetic material from the wild relative as possible while keeping the trait of interest. Molecular markers can be used to track the trait of interest through the crosses, a process called 'marker-assisted breeding'. However, introgression breeding is time consuming and technically challenging when more than one gene is being selected for, and it is often difficult to get rid of closely linked undesired genes. Given that introgression breeding does not involve genetically modified (GM) techniques, the product is not classified as a genetically modified organism (GMO) in the EU. **(B)** Transgenesis allows for the transfer of a desired gene from an unrelated organism into the domesticated crop. The process is based on the random genomic insertion into the crop plant of genetic material by the soil bacterium *Agrobacterium tumefaciens*. Typically, all of the inserted elements are transgenic. The gene in question is cloned into a binary vector system along with a selection marker and between short transfer DNA (T-DNA) border sequences of bacterial origin. Subsequently, *Agrobacterium*

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