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Science & Society

Q2 Genome-edited tree
crops: mind the
socioeconomic
implementation gap

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 13

14 The discussion about CRISPR/Cas
 15 genome editing is focused mostly
 16 on technical aspects to improve
 17 productivity and climate resilience
 18 in major tree crops such as cocoa,
 19 coffee, and citrus. We suggest a
 20 solution to the largely ignored so-
 21 cioeconomic impacts for farmers,
 22 when new genome-edited varieties
 23 are introduced from the laboratory
 24 to the field.

Genome-edited technologies in
sustainable agriculture

25 One third of the Earth's surface is used
 26 for agriculture to produce food, fibre,
 27 and bioenergy, but agriculture is also a
 28 major driver of environmental degrada-
 29 tion affected by and amplifying climate
 30 change. Consequently, there is increasing
 31 pressure for sustainable agricultural prac-
 32 tices to be included in major international
 33 policy initiatives [1], and it is recognised
 34 that sustainable agriculture will be critical
 35 to achieving the United Nations (UN)
 36 Sustainable Development Goals (SDGs)
 37 by 2030 (<https://sdgs.un.org/goals>).
 38

40 CRISPR/Cas genome editing (see
 41 Glossary) has the potential to be a
 42 powerful tool for agriculture to reduce
 43 poverty, hunger, and the environmental
 44 impact of agriculture [2]. Genome editing of-
 45 fers the possibility of precision modifications

at predetermined genome locations. Genome editing is more versatile and precise than **genetic modification (GM)**, and can also be less costly than traditional crop breeding or GM [3]. In this manuscript we discuss them as distinct technologies.

Soon, large-scale field deployment of genome-edited (GE) crops is likely, but technical and socioeconomic challenges still constitute an **implementation gap** when transferring GE varieties from the laboratory to the field. The technical challenges include potential imprecision (e.g., off-target mutations) when altering targeted genes [3], and government use restrictions due to GE safety concerns [4]. The socioeconomic implementation barriers for GE crops are likely most severe in perennial crops such as cocoa (*Theobroma cacao*), coffee (*Coffea* spp.), or citrus (*Citrus* spp.) compared with annuals, because these perennials are primarily produced by **smallholder farmers** and any investment or management decision has long-term consequences for farmers [4,5]. Surprisingly, the socioeconomic impacts (SEIs) of field implementation of GE perennial tree crops have received little attention to date.

Here, we address the SEIs for farmers, when GE perennial tree crops are transferred to the field. We propose a farmer-based approach to overcome these impacts. The goal of the proposed approach is to improve access to and increase benefits from GE tree crops for smallholder farmers (Figure 1).

GE tree crops – SEIs and farmer
uncertainties

CRISPR/Cas-based GE has recently been used to introduce disease and virus resistance, improve crop quality, and reduce breeding time in the smallholder-dominated crops cocoa, coffee, and citrus (Table S1 in the supplemental information online), but farmer uptake of the new GE varieties

Glossary

Agroforestry systems: a type of agricultural management that involves diversifying the tree crop plantation by establishing secondary crop and non-crop trees and annual plants to enhance soil fertility and carbon sequestration, provide shade for the main crop, and provide habitat for beneficial insects, and agrobiodiversity in general.

Climate-smart farms: farms that are carefully designed, in their plant structure and management regimes, to withstand climate change impact. For example, an appropriate selection of shade trees in cocoa, coffee, and citrus agroforests may buffer farm temperatures, and promote carbon sequestration.

Ecological resilience: the amount of disturbance that an ecological system can tolerate before moving into a new alternative stable state. In applied ecology, it can also refer to the capacity of a system to maintain its ecological structure and functioning after a disturbance process (e.g., pest and disease outbreaks or climate change).

Genome editing (GE): offers the possibility of precision modifications (i.e., removing, adding, or altering genetic material) at predetermined genome locations. Although knowledge on the risks of GE technology is still accumulating, the economic, environmental, and human health risks of GE appear to be lower than that for GM.

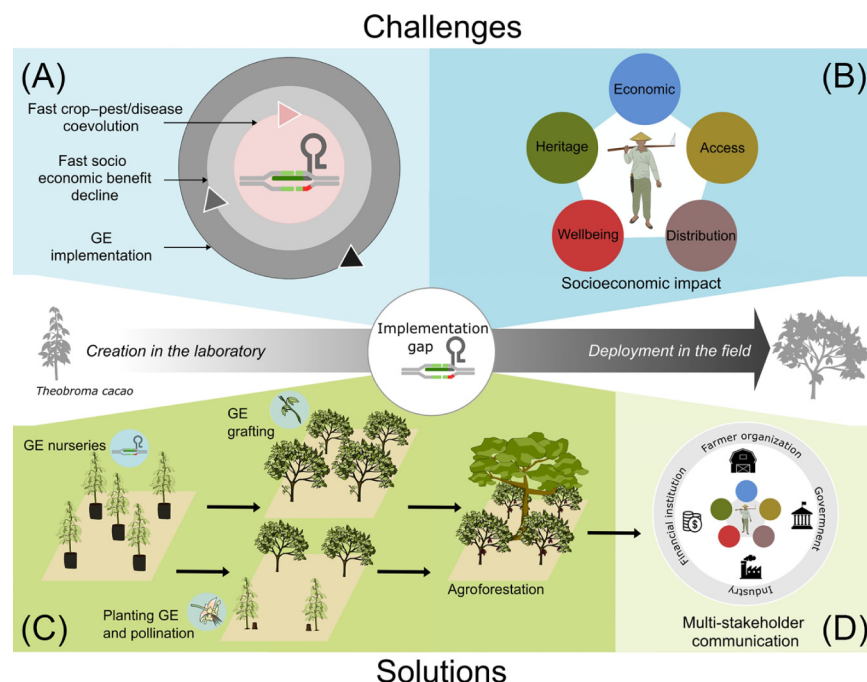
Genetic modification (GM): refers to the process of introducing foreign DNA into target organisms using biotechnology. GM has limited capacity to determine where in the genome the modification occurs. Sociopolitical resistance against GM crops is associated with socioeconomic and ecological trade-offs of early field-scale deployment of GM crops. For example, the introduction of GM maize and soybeans in Latin America has resulted in farm expansion and forest and agrobiodiversity loss, farm abandonment and food insecurity for smallholders, and sociopolitical instability.

Grafting: an agronomic technique designed to improve productivity in crops. It consists of using a vigorous plant tissue to replace the rooting system of a plant susceptible to stress factors, such as pests and diseases or temperature. The new upper part of the plant is called the scion, and the new rooting system is the rootstock.

Implementation gap: the time lag between the creation of a gene-edited crop variety in the laboratory and its transfer to the field. The implementation gap is associated with technical (such as coevolutionary pest pressures), and socioeconomic (such as economic, access and ownership, benefit distribution, wellbeing, and cultural heritage) challenges.

Interdisciplinary approach: integration of knowledge, methods, and tools from two or more disciplines to advance the understanding of a particular phenomenon, or to solve a problem that is beyond the scope of one single discipline.

Smallholder farmers: farmers operating on farms of <2 hectares.



Q1 Figure 1. An overview of the technical and socioeconomic implementation gap of genome-edited (GE) tree crops. Using cocoa (*Theobroma cacao* L.) as an example, a GE plant variety is created in the laboratory, but there is a time gap before implementation on the farm (grey arrow in the figure centre). Fast crop-pest/disease coevolution, in which pests evolve resistance to the GE variety likely occur before large-scale implementation of the GE variety. This leads to a cycle of updating the GE variety (modification of the gene editing to accommodate new resistance to the trait as it was first expressed in the GE variety) to respond to new pest resistance and declines of socioeconomic benefits for farmers (A) Five socioeconomic impacts (SEIs) critical for farmers are currently neglected during the GE variety implementation process, leading to further difficulties with large-scale adoption of GE technologies at the farm level: (i) economic, (ii) access and ownership, (iii) benefit distribution, (iv) wellbeing, and (v) cultural heritage (B) For details on the SEIs see Table 1 in the main text. A gradual and partial replacement of old trees with new GE varieties by grafting and enhancing pollination of GE seedlings in agroforests (agroforestation, C). This solution is suitable for a wide variety of tree crop species such as cocoa, coffee, and citrus. Multistakeholder efforts by financial institutions, industry, government, and farmer organisations, that highlight farmers' socioeconomic concerns and knowledge exchange will be crucial to support large-scale adoption of GE varieties at the farm level (D).

Trends in Ecology & Evolution

74 has been slow. We argue that this is
75 primarily for two reasons.

76 First, the SEIs for farmers including eco-
77 nomic, access and ownership, benefit
78 distribution, wellbeing, and cultural heri-
79 tage impacts have not received sufficient
80 consideration (Table 1) [5]. While these
81 five SEIs were previously identified in GM
82 crops, most SEI analyses have not differen-
83 tiated between GM and GE crops [4], have
84 focused primarily on economic impacts [6],
85 and have used industrial monocultures as
86 the reference system to assess the type

and extent of impacts [5]. For some annual
GE crops this approach may be sufficient,
but perennial tree crops such as cocoa,
coffee, or citrus require full consideration of
all five categories of SEIs. For instance, the
multiyear commitment of farmers for peren-
nial GE crop production has direct eco-
nomic, but also potential wellbeing, benefit
distribution, and access and ownership im-
plications. The risk of crop failure during the
lifetime of the crop trees is an economic con-
sideration and is at least partially dependent
on long-term coevolutionary crop-pest and
disease dynamics. These dynamics are a

known technical challenge of GE technology 87
but have not been analysed specifically 88
in terms of SEIs for GE perennial crops 89
(Figure 1A and Figure S1 in the supple- 90
mental information online). In addition, 91
long-term commodity price volatility can 92
necessitate a change in intercropping 93
strategies (e.g., cash crop and food crop 94
combinations) driven by local and inter- 95
national market demands in emerging 96
economies with downstream effects on 97
economic stability, food security, and 98
wellbeing. These shifts in intercropping 99
strategies can also affect benefit distribu- 100
tions at the household or community 101
level, particularly if there are gender differ- 102
ences in responsibilities for different crops. 103
In coffee, for example, women prefer 104
agroforests with fruit trees to meet house- 105
hold needs, while men may opt for timber 106
trees for economic benefits [7]. In regions 107
with uncertain land tenure, there is a risk of 108
new policies affecting farmer access and 109
ownership, which reduces the tenability of 110
crops that require multiyear commitment 111
(Table 1 and Table S2 in the supplemental 112
information online). 113

Second, economically marginal small- 114
holders in developing countries perceive 115
GE trees as an unproven long-term invest- 116
ment compared with established non-GE 117
trees [8] (Figure 1B). This is the case if the 118
farmer's established trees have provided 119
somewhat reliable income for instance 120
under variable climate, disease and pest, 121
economic and sociopolitical volatility [9]. 122
There is little incentive for these farmers 123
to remove existing trees and introduce 124
new GE varieties which are not yet field 125
proven and may be more expensive and 126
difficult to acquire due to property rights. 127
Thus, SEIs are amplified by the fact that 128
70% of global coffee and cocoa [10] as 129
well as most citrus in China, the largest 130
citrus producer globally [11], is produced 131
by smallholder farmers. These farmers are 132
strongly dependent on their land and the 133
specific social and economic structures are 134
highly crop and location dependent [5]. 135

Table 1. Five SEIs of GE crops for farmers

SEI key areas ^a	Specific impact of GE on	Description
Economic	Income stability	Price volatility in tree crops creates farmer income instability, and low investment margins. Farmers may require loans for GE deployment, causing financial dependence and debts.
	Land tenure	Uncertain land tenure schemes in association with the long-term investment risk in perennial crops (e.g., at least 3 years until first harvest in cocoa) jeopardises farmer income stability.
	Farm operational costs	Initial high operational costs for GE crop purchasing and inputs, and labour to deploy GE plant material and manage farms rely entirely on farmers' investment.
	Pest control	The respective evolution of pesticide and herbicide resistance in pests and weeds requires the purchase of updated GE plant material and inputs, causing a vicious cycle of financial dependence on biotechnology corporations.
	Human equity	The overall cascade of financial, land tenure, farm operational costs, and pest control impacts affect primarily the livelihoods of the least-favoured groups (i.e., women and children), and increases social inequity and the gender gap.
Access and ownership	Land tenure	Unregulated land tenure in cash crops creates unfavourable conditions among stakeholders, where powerful landowners and grabbers benefit at the expense of landless smallholders.
	Knowledge access/control	Both non-GE and GE seed and plant varieties, and intellectual property rights are generally controlled by large corporations, limiting their access to smallholders.
Benefit distribution	Human equity	The distribution of GE crop benefits differs between social groups, and are largely based on gender, age, economic status, or other social factors. Least favoured groups will likely be marginalised during the distribution of GE technologies.
Wellbeing	Human health	A possible shifting from staple to perennial cash crops, will have an impact on smallholder quality of life, including intersections with health impacts such as nutrition, disease, food security, and exposure to biocides.
Cultural heritage	Indigenous knowledge	Farming homogenisation (e.g., use of single GE varieties in monocultures), genetic contamination (i.e., in the case of GM crops) of local crop varieties affects culture and traditions of indigenous smallholders, and the loss of invaluable world human heritage.

^aPrevious research on GM crops has highlighted five key areas of SEIs to smallholder farmers [5], which is likely even more relevant for GE crops (see also Figure 1B in the main text, and reference list in Table S2 in the supplemental information online).

Addressing SEIs and bridging the implementation gap

We propose a technical and socioeconomic solution to bring GE crops from the laboratory to the field in smallholder farms, that can also be used in large-scale industrial farming and in rehabilitation of degraded lands (Figure 1C,D). Our solution builds on tree nurseries, grafting techniques, and agroforestry

systems to achieve a low ecological and socioeconomic risk for the environment and smallholders, based on a staged approach to GE tree deployment.

Grafting, plant nurseries, and agroforestry management

We propose nurseries growing GE plant materials (Figure 1C) that could be deployed through on-farm grafting of GE scions

(newly emerging shoots) onto existing old trees (Figure S2 in the supplemental information online). This would move the GE plants quickly into field production at low risk to the farmer because it is possible to retain the benefits of the existing trees combined with the additional benefits from the GE material. Moreover, when a GE scion is grafted, the new variety grows on the old rooting system and typically reaches fruiting stage more quickly. A GE plant nursery could hold numerous GE types with genetically diverse background genomes and different optimized traits, including pest resistances or tolerance to abiotic stress.

Grafting also can maintain high levels of genetic diversity at the farm level, which is useful to mediate coevolutionary crop-pest and pathogen dynamics [12]. GE seedlings could also be produced in the nursery and then gradually replace old trees in the plantation, where the seedling can grow under the shade of the remaining old trees. Yield losses in the first production year can be minimised through effective ecological tools such as hand pollination in cocoa, which has been shown to be an easy way to increase crop yields [13]. Plantations with high genetic diversity from the old trees and a diversity of GE scions would have economic and **ecological resilience**, provide stable income to farmers, and create **climate-smart farms** [9]. This approach allows continuity of production and stable accrual of socioeconomic benefits, including access to old genetic varieties, quick adjustments between cash (i.e., cocoa, coffee, and citrus) and food (e.g., fruit trees) intercropping, and may contribute to the understanding and access of farmers to GE technologies. In addition, crop diversification in agroforestry systems has positive effects on farmer mental health, may promote gender equality in farming tasks and income, and can improve food security in households of smallholder farmers [14]. Genome editing material introduction may

also benefit from the transition of monocultures and degraded lands to agroforestry systems.

Overall, the proposed program of grafting, CRISPR/Cas nurseries, and plantation diversification could reduce the socioeconomic cascade of problems associated with the implementation gap, including yield declines, low farmer incomes, the need for farm expansion, forest and biodiversity loss, and farm abandonment. Mitigating these problems could contribute towards achieving the agriculture-related UN SDGs: (i) no poverty, (ii) zero hunger, (iii) gender equality, (viii) decent work and economic growth, (xii) responsible consumption, (xiii) climate action, and (xvii) partnership for goals.

Multistakeholder engagement, interdisciplinary research, and the way forward

The adoption of the proposed CRISPR/Cas plant nurseries and grafting programme in agroforestry systems would help to bridge the socioeconomic and technical implementation gap in GE tree crops such as cocoa, coffee, and citrus under consideration of all SEIs (Table 1). However, the political, ecological, and sociocultural variability across the production range of these crops requires a multistakeholder perspective and full integration of farmers' needs, supported by the financial institutions, industry, governments, and farmer organisations to help farmers fully leverage the benefits from technology innovations (Figure 1D) [15]. From a research perspective, an interdisciplinary approach is critical where biotechnology experts developing GE tree

crops work closely with scientists from other disciplines (e.g., agroecologists, social scientists, and economists) to deliver technological and socioeconomic benefits of GE crops. Only through this multifaceted, multistakeholder approach will GE technology and next-generation agriculture unfold its full potential to increase global and local food security and secure farmers' livelihoods in an uncertain future.

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Declaration of interests

No interests are declared.

Author contributions

M.T.H. and T.C.W. conceived the idea for this manuscript and designed the figures. C.B. conducted the literature search. M.T.H., T.A.L., A.A., and T.C.W. wrote the paper. All authors commented on drafts and refined the final manuscript.

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