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Why new crop technology is not scale-neutral—A critique of the expectations for a crop-based African Green Revolution

Klara Fischer

Department of Urban and Rural Development, Swedish University of Agricultural Sciences, P.O. Box 7012, SE-750 07 Uppsala, Sweden

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ABSTRACT

Poverty reduction during the Asian Green Revolution has been attributed to the inherent scale neutrality of new crop varieties making them equally beneficial to small-scale and large-scale farmers. The term 'scale-neutral' is now reappearing in debates on agricultural development in Africa with claims that crop technology is inherently scale-neutral and that African smallholders will significantly benefit from new crop varieties not specifically developed for their contexts. Using a social shaping of technology (SST) perspective and the concept of biological embeddedness, this paper critically examines whether it is helpful to describe crop technology as scale neutral when drawing lessons from the Asian Green Revolution about how new crop technology can be of benefit to African smallholders. The paper describes how political commitment, rather than inherently scale-neutral crops, was central for the outcome of the Asian Green Revolution. It also highlights that while the effects of crop biology are often disregarded in adoption studies, biology significantly affected the ability of Green Revolution crop technology to benefit smallholders, and continues to do so today. Using maize and GM crops as examples, this paper suggests that GM crops in their current form have reinforced a technological trajectory established with hybrid technology and directed it away from smallholder practices and agroecologies. Consequently, describing crop technology as inherently scale-neutral is not helpful for understanding how crop technology works in Africa today and prevents important lessons being learned from the Asian Green Revolution.

1. Introduction

During the past decade, new crop technology[1] has been at the centre of debates on how to revitalise African smallholder agriculture. Parallels are frequently drawn with the so-called Green Revolution (GR) in Asia, where new varieties of wheat and rice (referred to interchangeably as high yielding varieties (HYV) or modern varieties (MV)[2]) introduced from the 1960s onwards proved to have significant poverty-reducing effects. These new crop varieties were described as scale-neutral, *i.e.* of equal benefit to large-scale and small-scale farmers (Feder and Umali, 1993; Feder, 1980). After two decades of inattention to agriculture in the global development community (Scoones and Thompson, 2011; McMichael, 2009), during which the term 'scale neutral' was seemingly dormant in the academic debate, the term is now reappearing in the debate on the potential of new crop varieties in general, and genetically modified (GM) crops[3] in particular, to benefit African

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E-mail address: klara.fischer@slu.se

[1] The term 'new crop technology' is used in this paper to refer to crop technology that has not previously been adopted by that farmer. During the Asian GR this new crop technology consisted mainly of new varieties of rice and wheat developed in particular to give higher yields. Today in the debate on how African farmers might benefit from new crop technology, this new technology refers both to various new traits inserted in crops through genetic modification (see footnotes 2 and 3 for further clarification) and new conventionally bred (not genetically modified) crop varieties.

[2] For the sake of clarity and consistency, this paper only uses the terms HYV or MV when discussing how other authors have used these concepts. However, because crop species and modifications are seldom specified in the literature, in many places in the paper it is impossible to accurately state the crop and modification in question. In these cases, the paper employs the terms 'new crop varieties' or 'new crop technology' when talking generally about new crop varieties, or GR crop varieties/GR crop technology when referring to varieties released during the Asian GR.

[3] According to the European Union regulatory framework on GMOs (DIRECTIVE 2001/18/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 12 March 2001 on the deliberate release into the environment of genetically modified organisms and repealing Council Directive 90/220/EEC), a genetically modified organism (GMO) means "an organism, with the exception of human beings, in which the genetic material has been altered in a way that does not occur naturally by mating and/or natural recombination". The GM crops referred to in this paper are the genetically modified (GM) crops that dominate the market today (herbicide-tolerant and insect-resistant (Bt) crops). These are transgenic crops, meaning that sections of DNA from another organism have been inserted into the plant's DNA in order to produce new traits. There are also cisgenic GM crops, where DNA fragments or genes

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smallholders.[4] It is being argued that as new crop technology is scale-neutral, it can be a key driver in the transformation of African smallholder agriculture (see e.g. Juma, 2013; Mosley, 2002; Wiggins et al., 2010; Qaim, 2009; Collier and Dercon, 2014). The fact that the Asian GR occurred under quite different circumstances seems not to temper these expectations. On the contrary, scale neutrality is frequently described as a function inherent in crops, seemingly unaffected by context. Collier and Dercon write in the present tense that "*most of these [HYV] are scale-neutral*" (2014, p.94). Qaim transfers the term to GM crops and state similarly that "*GM crops may also be well suited for small-scale farmers, because such seed technologies are scale neutral*" (2009, p.685). As exemplified in the abovementioned quotes, where crop species or genetic modification is not specified, it is also the rule rather than the exception for crop biology to be blackboxed in these discussions.

Crop technology has an important role to play in raising the productivity of agriculture in Africa today; however, for this to occur it must be appropriate for African farmers' practices and contexts (Scoones and Thompson, 2011). This requires a clear understanding of the function of any new crop technology *per se* and how the technology is co-shaped by its host crop, its end users and their contexts. This paper draws on literature, ideas and concepts from the field of social shaping of technology (SST) (Sørensen and Williams, 2002; Williams and Edge, 1996) and the concept of biological embeddedness (Russell, 2008) to critically explore the extent to which the term 'scale neutral' assists or hinders us in drawing lessons from the Asian GR when analysing the role of new crop technologies for African smallholders today.

Section 2 describes how SST in combination with the concept of biological embeddedness and farming systems research (FSR) is used here to analyse the social and biological influence at different scales on the interaction between new crop technology and smallholders. Section 3 draws on some of the influential literature on the Asian GR to describe how the concept 'scale neutral' was introduced to explain smallholder adoption of new crop technology during the Asian GR, while highlighting the acknowledged limitations of the term 'scale neutral' for describing what was going on. It goes on to point out factors shown to be important for the empirically observed scale neutrality. Section 4 discusses the re-appearance of the term 'scale neutral' in contemporary discussions on agricultural development in Africa and discusses the differences between the contemporary situation in Africa and the situation in Asia during the GR. It is highlighted how the increasingly privatised agricultural development regime, African land use characteristics and crop biology negatively affect the possibility for crop technology to work in a scale-neutral manner in Africa today. Section 5 focuses specifically on the framing of GM crops as scale-neutral in recent agricultural development debates. The talk of GM crops as scale neutral is placed in perspective by studying the empirical record on GM crops and smallholders today. This section shows how GM crops, rather than being scale neutral, can be usefully understood as a continuation and reinforcement of an established crop technological trajectory that started with hybrid technology. Conclusions are presented in Section 6.

2. Social shaping perspective to scale-neutral crop technology

In its broadest sense, the field of SST hosts research that in various ways demonstrates the social influence on technological change. It evolved from a critique of modernist perspectives on technology as artefacts with fixed functions, responding to objective problems in society (Sørensen and Williams, 2002). The literature describes three core features of SST, whereby it acknowledges the co-evolution of society and technology, the simultaneous negotiability (flexibility) and irreversibility of all technology, and the inherently political nature of technological development, since choosing one design and development trajectory over another has different implications for different social groups (cf. Williams and Edge, 1996; Sørensen and Williams, 2002).

It also adopts the term 'technological trajectory' (Dosi, 1982). Dosi (1982) concluded that technology outcomes are governed both by factors inherent to the technology and the external economic environment, and that technology not only consists of a set of physical devices (crops and their genetics in this case), but also of a set of disembodied (or discursive) factors such as the particular know-how, memories from past attempts, and ideas about future limitations and possibilities (Dosi, 1982, p.152). He developed the term 'technological trajectory', defined as "*the pattern of 'normal' problem solving activity (i.e. of 'progress')*" within a wider technological paradigm (Dosi 1982, p.152), where the technological paradigm governs how progress can be defined, and thereby limits the possible alternative solutions for defined problems.

Possibly as a result of its roots in sociological and historical research on technology, SST rarely includes biology[5] as an active part in shaping technology (see *e.g.* the complete lack of active nature in the anthology of SST research by Sørensen and Williams (2002)). However, the central role of biology in shaping living technologies, such as crop technology, is noted by Russell (2008), who draws on SST in analysing the biotechnology of GM cotton. Russell (2008) introduces the term 'biological embeddedness' to reflect the particular properties of technology that forms part of living biological entities. She describes biological embeddedness as "*both the literal embedding of a technology inside a living organism, and the metaphoric embedding of the technology in social, spatial and ecological settings by virtue of its biological nature*" (Russell, 2008, p.214).

Two particular dimensions of biological embeddedness described by Russell are drawn on here. First, the outcome of biologically embedded technology depends on the interactions between scientists' intentions, internal crop biology and the surrounding ecosystem. While Russell (2008) specifically talks about GM crops, this interaction between intentions, crop biology and ecology in shaping crop technological trajectories applies equally to any crop breeding activity (*e.g.* as outlined by Fitzgerald (1993) with regard to the development of hybrid maize). Second, as crop technology is generally able to reproduce itself, it is less dependent on the industrial production system[6] and therefore has greater

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are moved between organisms from the same species, but these are not discussed here.

[4] After the academic references to scale neutral in the 1980s and 1990s (e.g. Feder, 1980; Feder and Umali 1993), the concept seems to have been fairly dormant until it reappeared in literature discussing crop technology in the 2000s (Mosley, 2002; Hazell et al., 2010; Wiggins et al., 2010; Collier and Dercon, 2014). With some time lag in relation to societal events, which is in the nature of academic work, this follows the general trend of the shifting centrality of agriculture in development policy over time. In sharp contrast to the attention given to crop technology during the Green Revolution in the 1960s and 1970s (and appearing in the academic literature up until the early 1990s), the role of agriculture in rural development was largely ignored throughout much of the 1980s and 1990s in the global development community (McMichael, 2009; Scoones and Thompson, 2011). This trend shifted at the start of the millennium (Andersson Djurfeldt, 2013), which can be seen in reports such as the publication *Agriculture at the Crossroads: International Assessment of Agricultural Knowledge* (Kiers et al., 2008) commissioned by the World Bank and the Food and Agriculture Organization (FAO), and the fact that the *World Development Report 2008: Agriculture for Development* (World Bank, 2007), was the first world development report in 25 years to be devote d to agriculture (McMichael, 2009).

[5] The term biology is used here to include all biological functions of the world from genetics to ecosystems.

[6] I here draw on Russell (2008, p. 215) to define industrial production system as the factory (or in the case of crops, e.g. the laboratory or research station) where a technology is developed.

potential than many other (non-living) technologies to be shaped by its end users. Russell (2008, p.215) writes that "biologically embedded technologies are potentially disconnected from the industrial production system and embedded in local contexts, because the production system is inside the plant, not in a distant factory". Nevertheless, she notes that the extent to which crop technology can be freed from its industrial production system also depends on societal regulation of the technology (Russell 2008).

By introducing the concept of biological embeddedness, Russell (2008) takes a first step towards integrating biology as an active agent in shaping living technology. However, while acknowledging that living technologies are particularly prone to result in outcomes that are not predicted, Russell (2008) only analyses GM cotton technology on the basis of the intended effects of the genetic modification (herbicide tolerance or insect resistance). The importance of unpredicted consequences of crop technology is highlighted in other studies based on a more comprehensive understanding of crop biology, where it has been shown that smallholders experience outcomes of GM crop technology that go beyond the intended effects of the genetic modification. For example, South African smallholders growing HT and Bt maize have ascribed changes in drought tolerance and reduced tolerance to storage pests, features that do not obviously relate to the genetic modification (Jacobson and Myhr, 2013; Fischer and Hajdu, 2015; Assefa and Van Den Berg, 2009).

A more comprehensive understanding of the effects of biology would enable fuller acknowledgement of the biological shaping of crop technology. In this paper, the integration of biology as a key factor in shaping crop technology is taken further by drawing lessons from FSR (Chambers et al., 1989; Scoones and Thompson, 2009; Pretty, 1995). The field of FSR provides extensive empirical evidence of the co-effects of farmers' practices, agroecology[7] and crop biology in shaping technological trajectories (Mercer et al., 2012; Li et al., 2013; Dawson et al., 2008; Morris and Bellon, 2004; Puente-Rodriguez, 2008; Wassmann et al., 2009). Much FSR has focused on smallholder farming, and an important lesson from this research is that as the rural poor are often confined to living in environments in which they are exposed to multiple environmental and social uncertainties and dynamics, the outcomes of introducing crop technology are also often more unpredictable in these contexts (Jacobson, 2013; Dawson et al., 2008). Incorporating the lessons from SST, a structural and political dimension is added to this. This paper thus extends the social-shaping perspective to technology and acknowledges that crop technology is socially shaped at different scales, being affected by *e.g.* market structures, policies and regulations and individual farmer behaviour, and by agroecosystem dynamics as well as the particular genetic set-up of a specific crop variety.

3. Scale-neutral crop technology during the Asian Green Revolution

Although the smallholder-related impacts of the GR differed across Asia and varied over time, overall (and often in contrast with Africa) it has been acknowledged as a success with regard to new crop technology reaching smallholders (Djurfeldt et al., 2005; Hazell, 2009; Evenson and Gollin, 2003). The following sections contain an analysis of how the term 'scale neutral' enters academic discussions on smallholders and crop technology in the GR literature. The publications that have now reintroduced the term 'scale neutral' for drawing parallels between the Asian GR and what is the hope for Africa today seldom refer to where the concept comes from (see e.g. Wiggins et al., 2010; Mosley, 2002; Hazell et al., 2010; Collier and Dercon, 2014). Thus it has not been possible to trace the concept back to the original literature. However extant research indicates that publications by Feder et al. (1985), Feder et al. (1982), Feder (1980), Feder and O'Mara (1981) on farm size and GR technology adoption provide much of the theorisation on scale-neutral crop technology in relation to the Asian GR. Also, the book "*New Seeds and Poor People*" by Lipton and Longhurst (1989) was found to be seminal in studies on the poverty reduction effects of the Asian GR (see e.g. Das, 2002). The abovementioned publications also review a large body of empirical evidence on smallholder adoption of new crop varieties during the Asian GR. Other publications are included in the analysis when relevant for enriching description of the findings.

A study of this body of literature reveals that, despite the centrality of the term in much of the literature discussing the GR, the meaning of scale neutral is not explicitly defined. It is commonly stated as fact, and in passing, that MVs or HYVs are scale neutral, without defining what is meant by this (see *e.g.* Lipton and Longhurst, 1989, p.126, 143). Even in the more technical literature, scale neutral is not clearly defined, although it is repeatedly linked to being divisible (Feder et al., 1985; Feder and O'Mara, 1981; Feder and Umali, 1993). Feder and O'Mara (1981, p.59) state with regard to HYV that "*the technology is divisible and neutral to scale*". Feder et al. (1985, p.270) state that "*the Green Revolution and farmers' responses to it are relevant as examples of innovations* [later specified as HYV] *that are divisible and thus neutral to scale*". Divisible inputs are defined as those that can be divided without extra costs and used on small farms or small parts of a farm. Indivisible inputs are *e.g.* tractors or irrigation systems, where the cost is not obviously possible to divide, favouring large farms due to economies of scale (*c.f.* Feder et al., 1985).

However, what appears to be missing in the recent literature that has re-introduced the term 'scale neutral' is that in fact Feder et al. (1985) go on to acknowledge that referring to HYVs as scale neutral is of limited help when trying to understand precisely what allowed many smallholders to benefit from them during the Asian GR. Firstly, it is noted that HYVs are connected with other inputs, such as irrigation, that might not be equally divisible (see e.g. Feder et al., 1985, p.280). Secondly, despite farm size being central to the specific definition of scale-neutral as being divisible, Feder et al. (1985, p.272) state that "*absolute farm size may be noncomparable across countries or regions because of differing agroclimatic conditions*" and, furthermore, that "*[t]he wide variety of empirical results, interpreted in the context of the theoretical literature, suggests that size of holding is a surrogate for a large number of potentially important factors such as access to credit, capacity to bear risks [. . .], access to scarce inputs (water, seed, fertilizers, insecticides), wealth, access to information, and so on.*" (Feder et al., 1985, p.273). It can thus be concluded that, while GR literature indeed connects the term 'scale neutral' to new crop varieties (alternatively referred to as HYVs or MVs), it makes little use of the term when actually explaining why smallholders under some circumstances benefited from the new crop varieties. In fact, the limitations resulting from using the term to explain empirical results are clearly acknowledged. While the early literature clearly suggests that crop-technology is not inherently scale neutral, the empirical account of the Asian GR however shows how the social and biological shaping of GR crops sometimes had scale-neutral outcomes. The following sections discuss the key social and biological factors identified as being of importance for the scale neutrality observed.

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[7] Agroecology in this body of literature encompasses all the environmental factors that interact with the crop such as soil, climate and insects.

3.1. The importance of financial and advisory support for crop scale neutrality in Asia

When describing the success of the Asian GR, the single most frequently mentioned factor is probably the significant grants provided to make the new crop technologies affordable to smallholders (Pingali, 2012; Evenson and Gollin, 2003; Hazell, 2009). It is clear from the literature that only when credit constraints were eliminated could the new crop technology be of benefit to smallholders. Feder and colleagues (Feder et al., 1982, 1985; Feder and O'Mara, 1981) present a variety of empirical examples where credit constraints led to limited smallholder adoption of new crop varieties, also during the Asian GR. The importance of credit in the success of the Asian GR and the fact that smallholders are commonly more credit constrained than large farmers indicate that poverty is an important characteristic of smallholders. Indeed apart from a lack of money, access constraints more generally as well as risk aversion, which were found to be key factors affecting smallholder adoption of GR crop technology in Asia (Feder, 1980; Feder et al., 1985; Lipton and Longhurst, 1989) are also key characteristics of poverty (*c.f.* Sen, 1981; Mosse, 2010). The close connection between being poor and having a small farm in the GR literature is illustrated by the way in which Lipton and Longhurst (1989) conflate small and poor farmers throughout their book (while at the same time illustrating the fact that poverty remains under-theorised in the GR literature (*c.f.* Das, 2002)).

A factor that did benefit Asian smallholders was, in relative terms, their better access to and control over cheap (family) labour than large farmers. The new varieties of wheat and rice introduced during the GR were more labour intensive than the 'traditional' varieties used previously by farmers, as they required more labour for weeding, applying chemicals and harvesting the higher yields. Indeed, labour was the only factor empirically proven to favour Asian smallholders when adopting new GR varieties, and it applied only as long as the new crop varieties were not accompanied by labour-displacing technology such as tractors, herbicide sprayers or combine harvesters (Feder et al., 1985, 1982; Lipton and Longhurst, 1989). In contrast, risk aversion is described in the GR literature as limiting smallholder adoption of the new crop varieties. Feder et al. (1985, p.298) attribute smallholders' risk aversion explicitly to a lack of an economic buffer and state with reference to Arrow (1971) that "*it is generally accepted that absolute risk aversion declines as wealth increases*". The literature mentions subjective and objective risk. Subjective risk relates to not having sufficient knowledge to assess a new technology. As smallholders are generally not as well supplied with agricultural advisory services and information on new products as large-scale farmers, their behaviour is generally more greatly affected by subjective risk (Lipton, 1978; Feder, 1980). Investments in government advisory services during the Asian GR did not eliminate these differences (Pingali, 2012), but were important in reducing them and making the new crop technology increasingly useful for smallholders (Hazell, 2009).

As the paragraphs above indicate, while often not said explicitly in the GR literature, poverty related constraints are important for explaining how smallholders related to crop technology during the Asian GR; perhaps more so than farm size. The analysis of the literature also indicates that, rather than being a result of the introduction of inherently scale-neutral crop technology, the scale-neutral effects of the technology depended in particular on investments made by governments and international organisations in making the technology accessible and affordable to resource-constrained farmers as well.

3.2. FSR highlights the biological shaping of crop scale neutrality

While the earlier section has discussed subjective risk, objective risk relates to the direct link between risk aversion and wealth as suggested by Feder et al. (1985). The poor have limited economic margins to cope with various uncertainties and limited possibilities to make investments to improve their situation. The environments inhabited by many smallholders are also acknowledged to increase objective risk. Indeed, Feder and Umali (1993) cite agroecological factors as being most significant in explaining differences in the adoption rates of new crop varieties during the Asian GR. Drawing on FSR helps highlight the close interplay between social and environmental factors in affecting smallholder access to and benefit from crop technology. As a result of the marginalisation associated with poverty, many smallholders farm less optimal land characterised by e.g. infertile soil, deficient or excess rain etc. (Altieri et al., 2011; Dawson et al., 2008). Such environments increase the (objective) production risk (Feder et al., 1985), which can be reduced by stabilising production through inputs (such as fertiliser and irrigation) or spread by nurturing diversity (*e.g.* planting genetically diverse crops, diversifying livelihood options etc.) (Darnhofer, 2010; Bacon et al., 2012; Kremen et al., 2012; Dawson et al., 2008). As resource-constrained smallholders are generally less able than large-scale farmers to invest in agricultural inputs to stabilise production, they more frequently spread the risk by diversifying (Jacobson, 2013).

The first GR varieties released were not bred with smallholders in mind, but to give high yield on well-fertilised soils with a regulated water supply (Feder et al., 1985; Feder and O'Mara, 1981). By virtue of their standardised breeding process, the GR varieties were also more genetically homogeneous than traditional varieties, which meant that overall they were less capable of withstanding environmental dynamics than the more genetically heterogeneous traditional varieties. This increased the objective production risk for smallholders who were unable to provide such optimal agricultural circumstances (Feder, 1980). Two factors are cited in the literature as important in changing this and making the new crop varieties beneficial for smallholders. Firstly, the significant grants for irrigation and fertiliser provided by governments and international agencies during the Asian GR have been ascribed key importance in reducing smallholder production risks by providing a more stable production environment (Pingali, 2012). Secondly, it has been argued that it was only with the breeding of more location-specific crop varieties with better pest and disease resistance during the later parts of the GR that significant smallholder benefits emerged (Byerlee, 1996; Lipton, 2007; Evenson and Gollin, 2003).

Despite the evident importance of crop biology for the outcomes of adoption, the actual crops concerned are, however, severely neglected in the adoption literature. Feder and O'Mara (1981, p.62) state explicitly that "*The terms* '*new technology*', '*modern crop*', '*innovation*', *and* '*high-yielding variety-HYV*' *will be used interchangeably*". Lipton and Longhurst (1989) talk exclusively about MVs, but when doing so they refer to several publications that use the term HYV. Likewise, crop species are rarely specified in the literature. Feder et al. (1985), who use empirical evidence presented in other studies to draw conclusions about smallholder adoption of new GM crop varieties, clearly do not view crop species as an important factor affecting adoption. While the references drawn on are often more specific (in the reference list, rice is mentioned 21 times and wheat five times), Feder et al. (1985) only specify species five times in their paper (one reference is made to wheat and four to rice). In comparison, the unspecific term HYV appears 43 times and "modern crop" six times. The focus on increasing yield that is inherent in the term HYV and the general statement of HYVs as scale-neutral also overlook the fact that the early GR varieties, which were bred with a

Table 1
Key outcomes of the social and biological shaping of crop technology during the Asian GR.[a]

GR crop technology	Outcome	Social/biological shaping	Outcome
. . .needed new inputs (*e.g.* fertiliser) and increased production costs (Lipton and Longhurst 1989).	Comparative advantage for large farmers.	Wheat and rice seed can be shared and recycled (Hazell 2009). Investments in supplying credits to smallholders (Feder et al., 1985).	Comparative advantage for large farmers reduced.
. . . needed new inputs and practices and thus new knowledge (Feder 1980).	Comparative advantage for large farmers.	Investments in advice to smallholders (Hazell 2009).	Comparative advantage for large farmers reduced.
. . . required adoption of irrigation (Feder et al., 1985).	Comparative advantage for large farmers.	Investments in irrigation infrastructure for smallholders (Hazell 2009).	Comparative advantage for large farmers reduced.
. . . were more labour intensive (Feder et al., 1982; Lipton and Longhurst 1989).	Comparative advantage for small family farmers.	Family labour widely available (not absorbed by other sectors) (Lipton and Longhurst 1989).	Small family farmers had a comparative advantage.
. . . were initially not adapted to smallholders' agroecologies (Byerlee 1996).	Comparative advantage for large farmers.	Later investments in breeding for smallholder environments (Byerlee 1996; Evenson and Gollin 2003). Investments in supplying credits for fertiliser and providing irrigation (Pingali 2012).	Comparative advantage for large farmers reduced.

[a] For reasons of space, one central reference is provided for each statement, although several sources often mention the same factor.

narrow focus on yield, did not significantly benefit smallholders (Byerlee, 1996).

While rarely mentioned, choice of crop was an important factor for success in smallholder adoption. The dominant GR crop species introduced in Asia, wheat and rice, are self-pollinating crops. Seeds from such crops retain their genetic and physiological identity over generations (Morris, 2002). Farmers adopting the new wheat and rice varieties introduced during the Asian GR thus in effect only had to purchase seed once. The fact that seed could be recycled and shared between farmers has been acknowledged as a central factor in making the GR varieties useful to smallholders (Hazell, 2009). The possibility of freely recycling and sharing seed also meant that the crop technology was largely decoupled from its industrial production system (*c.f.* Russell, 2008), which significantly facilitated the spread of the GR crop varieties (Hazell, 2009).

To sum up, early references to the term 'scale neutral' actually point out that the term has little to do with features inherent in the crop (particularly since the new crops came with a need for new inputs), and that it is only vaguely connected with farm size (Feder et al., 1985). The section however also describes how the empirical record of the Asian GR indicates that GR crop technology sometimes had scale-neutral effects in practice. Table 1 summarises how outcomes of crop technology and its social and biological shaping during the Asian GR were sometimes scale neutral, mainly due to societal investments reducing the comparative advantage to large farmers.

4. Does scale-neutral crop technology occur in Africa today?

After having been dormant since the early 1990s (Feder and Umali, 1993: and footnote 4), the concept 'scale neutral' is now being reintroduced in academic discussions about how lessons can be drawn from the Asian GR on the role of new crop technology for African smallholders (Wiggins et al., 2010; Juma, 2013; Collier and Dercon, 2014). In these discussions, scale neutrality is frequently described as a function inherent in the crop, which remains unaffected by context. Mosley (2002, p.697), for example, states when discussing crop technology for African smallholders that "*modern varieties are scale-neutral—they do not require large areas or accompanying indivisible inputs in order to raise yields*". The use of the present tense in this quote and the lack of specificity about the 'modern varieties' referred to represent a common way of using the term in these academic discussions (Juma, 2013; Collier and Dercon, 2014, p.3) and indicate that the perspective is that crop biology and technology have not changed since the Asian GR and that context does not matter for their shaping.

As described in Section 3, however, empirically observed scale-neutral effects during the Asian GR were not due to inherent scale-neutral technology, but to its social and biological shaping. The following sections describe how contextual factors, crop species and technologies proposed for Africa today differ from those observed during the Asian GR. The effect of these differences is that the possibility for crop technology to function in a scale-neutral manner is lower today in Africa than during the Asian GR.

4.1. *Crop technology and African societies in a contemporary global context*

Firstly, it can be noted that labour availability, the only factor favouring smallholder adoption of new crop varieties during the Asian GR (Table 1), is not a factor inherently connected with small farms (Ellis, 2000; Lipton and Longhurst, 1989). Both Feder et al. (1985) and Lipton and Longhurst (1989) acknowledge that the introduction of GR crop varieties was unlikely to have the same effect in many African settings as it had in Asia, as smallholder systems in Africa more frequently suffered from peak-season labour scarcity (Feder et al., 1985; Lipton and Longhurst, 1989). Today labour is often not a constraining factor *per se*, but for historical and cultural reasons young unemployed Africans are often unwilling to engage in farming (Hull, 2014). An important reason for this is that they do not see farming as a way to escape poverty (White, 2012). The decline in government funding for agriculture that has occurred during recent decades can be seen as a partial reason for this. It has been shown how rural African households, and especially women and youth within these households since the 1980s, have diversified out of agriculture as a response to the lack of opportunities within the sector (Bryceson, 2002; White, 2012).

As described in Section 3, provision of credit, irrigation and advice was of key importance in allowing Asian smallholders to benefit from the GR crop varieties. Such support is recognised as being equally important for allowing African smallholders to benefit from agricultural technology today (Smale et al., 2013). However, the public sector in many African countries nowadays has a much more limited capacity to deliver this compared with during the Asian GR (Poulton et al., 2010; Scoones and Thompson, 2011; IIED, 2014). Public spending on agriculture in Africa today (on average just over 2.5% of the national budget (FAO, 2016)) is far lower than in Asia during the GR (up to 20% of the budget (Rosegrant and

Hazell, 2000)).[8] Referring to crop technology as scale neutral today clearly obscures this significant difference in agricultural support to smallholders between contemporary Africa and Asia during the GR.

The African situation follows a global trend of public sector withdrawal from agricultural development (FAO, 2016). Publicly funded research and crop development has reduced significantly worldwide since the Asian GR (FAO, 2016). At the same time a trend of merger and acquisitions in recent decades has resulted in a significant concentration of the private seed sector (Bonny, 2014). Bonny (2014) provides figures showing that the top ten seed companies in the world in 1985 controlled 12% of global seed sales, rising to 59% in 2012. In 2006 five large multinational seed companies together spent 18-fold more on agricultural research than the publicly funded CGIAR system (Leach and Scoones, 2006). The increasing corporate domination of crop technology is coupled with a global trend of rising seed prices, as well as regulatory and policy changes strengthening the possibility for crop technology developers to protect their inventions and at the same time weakening farmers' rights to the seed (Kloppenburg, 2014; Jefferson et al., 2014). The farmer-to-farmer seed exchanges which were important for spreading the new crop varieties during the Asian GR (Hazell, 2009) are now increasingly limited by law in many countries (Netnou-Nkoana et al., 2015).

The limitations on farmer-to-farmer seed exchange resulting from regulatory changes place greater demands on the formal seed distribution system in making new seed available. At the same time, the global tendency since the Asian GR of significantly reducing the role of the public sector in seed delivery means that in particular smallholders farming more marginal agricultural environments, where returns on investment for private companies are limited, are increasingly unlikely to be reached by the formal system (Scoones and Thompson, 2011; Odame and Muange, 2011; Rivera and Alex, 2004). Following the general trend of a withdrawing public sector, government-supported agricultural advice has also been significantly reduced in many countries during recent decades. This limited government investment in agricultural advisory services has obvious negative implications as regards smallholder exposure to subjective risk in relation to crop technology adoption (Tripp, 2001). The need to substantially increase the availability and quality of agricultural advice to African smallholders has been repeatedly emphasised in recent years (Smale et al., 2013; Hebinck et al., 2011; Friis-Hansen and Duveskog, 2012).

4.2. *Crop technology, African agroecologies and climate change*

As seen in Section 3.2, marginal environments have been acknowledged as posing a key challenge in allowing smallholders to benefit from the new GR crop varieties (Feder and Umali, 1993). This was in part overcome during the later stages of the Asian GR by adapting new varieties to these environments (Byerlee, 1996; Lipton, 2007; Evenson and Gollin, 2003) and by substantial investments in irrigation. The availability of irrigation has been acknowledged as a central factor in making the new GR varieties useful to Asian smallholders (Feder and Umali, 1993). Thus, the lack of irrigation in combination with the even more marginal and varied environments of many African smallholders compared with their Asian counterparts has been acknowledged as an important reason for the continuing absence of an African GR (Evenson and Gollin, 2003; Lipton and Longhurst, 1989). In future, it is predicted that many African farmers will be particularly hard hit by climate change (Boko et al., 2007), further stressing the need to consider robustness to withstanding stress when breeding crops for African smallholders. This need for robust varieties suitable for marginal environments is unlikely to be filled by the private sector now dominating crop development. The fact that the companies controlling agricultural research and development (R&D) are becoming fewer in number and larger has led to a general decline in the range of crop varieties available on the market and an increasing focus on the crops and varieties that are most profitable to these companies (Renwick et al., 2012; Howard, 2009; Newell and Mackenzie, 2004).

While crop biology has implications for the extent to which new crop technology can be of use to smallholders, the tendency in the GR literature for not clarifying what is meant by MV or HYV and seldom specifying crop species persists in the contemporary literature on African agriculture (see *e.g.* Mosley, 2002, p.697ff; Collier and Dercon, 2014, p.94). Doing so obscures the fact that resource-constrained smallholders often place different demands on crop performance than large-scale commercial farmers, *e.g.* as regards robustness to weather dynamics (Soleri et al., 2008; Chimonyo et al., 2014). Likewise, it obscures the fact that a key reason why African smallholders did not benefit from a GR was that the species introduced in Asia (wheat and rice) are not staple food crops for many Africans (Lipton and Longhurst, 1989). To highlight crop biology's relevance to crop technology, the example of maize is instructive. While there are many crops of relevance to African smallholders, maize, which has become the dominant staple crop in Africa, is given a central role in the promise of an African GR (Brooks et al., 2009). In contrast to wheat and rice, maize is an open-pollinating species. This means that if farmers do not take measures to control pollination, all second-generation maize plants in a field will differ genetically and physiologically both from the parent generation and from each other (Smale and Jayne, 2003). Farmers who want to maintain the high yields of the new maize varieties must therefore buy new seed regularly, which makes it easier for seed companies to make a profit from maize than from wheat and rice. This is particularly true for hybrid maize. Open-pollinated (non-hybrid) varieties may experience a yield drop if recycled for many generations, but hybrid seed in essence needs to be renewed every year to maintain yield. Because of this, hybridisation has been called ' the biological patent' (Kloppenburg, 2005, p.319); and it has been shown that the introduction of hybrid seed can significantly shift the control of breeding from farmers to the commercial breeding industry (Glenna and Cahoy, 2009). Since hybrid technology makes it possible for companies to make significantly more profit, private seed companies have focused their R&D efforts on hybrids. They have also focused on where the market is, *i.e.* among large-scale commercial farmers (Fitzgerald, 1993; Heinemann et al., 2013).

A biological result of hybrid seed development is genetic homogeneity. Other factors strongly associated with hybrids, such as high yields, high responsiveness to fertiliser *etc.*, are a result of a contingent technological trajectory directed at large-scale farmers (Fitzgerald, 1993; Jacobson, 2013; Kutka, 2011). The public efforts to develop maize hybrids suitable for smallholders in many African countries after independence (*e.g.* with better storability and drought resistance) show that other technological trajectories are possible (Smale and Jayne, 2009). However, these public sector

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[8] Fan and Saurkar (2006) studied data on government spending in 44 developing countries between 1980 and 2002 and found that in almost all regions governments had reduced the spending share on agriculture and on infrastructure. In Africa, government spending on agriculture declined from 6.42% of total government spending in 1980 to 4.42% in 2002, in comparison with a higher starting point, but more significant decline, in Asia, falling from 14.80% to 8.60%. The FAO statistics on government expenditures on agriculture (FAO, 2016) show that during the 2001–2012 period, government spending on agriculture relative to total government spending has fallen further across the world, with Africa being the region experiencing the biggest decline in the agriculture share of government expenditures, falling from a high of 4.5% in 2001 to just over 2.5% in 2012. This can be compared with figures provided by Rosegrant and Hazell (2000) on the share of total government expenditure during the Asian GR. In 1972 the Indian government spent 22.1% of its total budget on agriculture, declining to 11.5% in 1990, the same overall figure for Asia as a whole being 15% in 1972 falling to 9.6% in 1990.

efforts have not been sustained since the 1990s and maize R&D has increasingly passed to the private sector (Smale and Jayne, 2009; McCann, 2011).

The fact that distribution of (hybrid) maize technology depends more on the formal seed system than was the case for rice and wheat shows the importance of analysing the interplay between biological and societal factors in understanding the outcomes of crop technology. It also indicates that support to smallholders in terms of infrastructure, credits and agricultural advice might be even more important when dealing with maize than when dealing with rice or wheat.

5. Can GM crops be meaningfully analysed as scale-neutral technology?

Since the Asian GR, GM crops have entered the market amid discussions about how to improve smallholder farming. The term 'scale neutral' has also emerged in this context, where it is generally used to emphasise how easy it would be for smallholders in general and African smallholders in particular to adopt GM crops (see e.g. Herring, 2015; Thirtle et al., 2003; Scoones 2008). For example, in a recent CNN interview about how biotechnology can help African smallholders, Juma (2013) stated that GM crops are scale-neutral because they are grown by both large-scale and small-scale farmers (Juma, 2013: interview CNN). In the same interview, he referred to the ease with which these crops can be adopted by smallholders thus: "*The technology is embodied in the seed so all the farmer needs to know is that this seed has a technology inside it so that you don't need to spray pesticides*". Again referring to scale neutrality as being inherent in the crop, and without providing any definition of the term, Qaim (2009, p.685) writes that "*GM crops may also be well suited for small-scale farmers, because such seed technologies are scale neutral*". These quotes show how both crop biology and context again are made unimportant for the alleged scale-neutral effect of new crop technology.

While some scholars express significant expectations for GM technology to be of benefit to African smallholders (Wambugu, 1999; Juma, 2011; Morse and Mannion, 2009; Klümper and Qaim, 2014), there is still limited experience of GM crops planted in African smallholder systems. South Africa, Sudan and Burkina Faso are the only African countries where GM crops are grown commercially (James, 2014). It is therefore premature to claim that GM crops behave in a scale-neutral way in African contexts. However, by analysing the existing evidence on GM crops and smallholders from around the world, we can map the current main technological trajectories and analyse how these affect the possibility of GM crops to work as scale-neutral technology in different contexts. The analysis of the scale neutrality of GM crops presented here draws on evidence from South Africa (Jacobson, 2013; Jacobson and Myhr, 2013; Fischer and Hajdu, 2015; Kruger et al., 2011; Gouse, 2012; Thomson, 2008), China (Ho et al., 2009; Rao and Dev, 2009; Van Zwanenberg et al., 2011; Pemsl et al., 2005; Zhang et al., 2012), India (Lalitha et al., 2009; Shah, 2008; Stone, 2004, 2011; Herring, 2007) and Argentina (Van Zwanenberg and Arza, 2013; Van Zwanenberg et al., 2011).

The common GM crops today are herbicide-tolerant (HT) crops, insect-resistant (Bt) crops and crops containing these two traits combined (stacked-trait crops). The clearest argument against grouping these different GM crops together as scale neutral might be the widespread evidence that herbicide tolerance stimulates monoculture production and increased mechanisation, and thus the scaling up of agricultural units (Van Zwanenberg and Arza, 2013; Otero and Pechlaner, 2005; Binimelis et al., 2009). This is not the obvious outcome of Bt crops, which have been shown to bring higher yields due to reduced losses to insects in some smallholder systems (Stone, 2011; Gouse, 2012). However, as will be discussed here, the way in which the dominant technological trajectory for GM crops currently works means that Bt crops too might be of limited long-term benefit to smallholders.

As will be described here, the increased corporate control over crop technology, and the resulting focus on serving large-scale, capital-intensive farmers that started with hybrids (Fitzgerald, 1993 and Section 4.2), has proven to be further strengthened by GM technology (Heinemann et al., 2013; Parfitt, 2013). Private companies today are able to increase their control over the seed market in many jurisdictions by patenting DNA sequences. Kloppenburg (2014) describes the mutually reinforcing process whereby the possibility to attach patents to GM crops (in contrast to conventionally bred crop varieties) has concentrated the might of the seed industry and given it the power to effectively lobby for the spread and reinforcement of intellectual property rights. As a result, in many countries the introduction of GM crops has meant further restrictions on how farmers can use seed, as well as significantly increased seed costs (Parfitt, 2013). This in effect reduces the possibility for the technology to act in a scale-neutral manner.

South Africa, the only African country with a significant adoption of GM crops (James 2014),[9] reflects this wider trend whereby a comprehensive regulatory regime has strongly shifted power over seed away from farmers and into the hands of private companies, which have focused on delivering crop technology suitable for large-scale farmers (Jacobson, 2013). While a significant number of maize varieties on the South African market are suited to more heterogeneous and low-input smallholder systems, the industry has not prioritised breeding the GM traits into these varieties (Fischer and Hajdu, 2015). In addition, GM crops are patented property, and corporate control over GM seed is reinforced by the application of contract law. Farmers have to sign Technology Stewardship Agreements with the industry whereby they agree to refrain from recycling and sharing GM crop seed (Thomson, 2008). This has not limited the adoption and profitability of GM maize and cotton in the large-scale commercial farming sector in South Africa, where GM maize varieties are now more common than conventional maize varieties (Gouse, 2012). However, the combination of a reduced variety of seed available to farmers, the ban on farmers adapting commercially available GM crops to local environments, and the substantial rise in seed prices has been shown to significantly impede the usefulness of GM crops to the more resource-constrained South African smallholders (Jacobson and Myhr, 2013; Fischer and Hajdu, 2015). The technological trajectory of GM crops in South Africa has thus clearly not resulted in the technology having scale-neutral effects.

The South African situation can be contrasted with how GM crops have been introduced in China and India, where governments have opposed the global trend and actively taken action to make GM crops available and useful to smallholders to a greater degree. China has prioritised government-funded development and commercialisation of Bt cotton varieties and has licensed the Bt technology to a large number of small seed companies (Ho et al., 2009). These measures have made the technology more affordable and accessible to a wider group of Chinese farmers (Rao and Dev, 2009; Ho et al., 2009). In India, the government has aimed at retaining farmers' rights to seed and there are many examples of the government

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[9] According to James (2014), South Africa is the ninth largest grower of GM crops in the world after the US, Brazil, Argentina, India, Canada, China, Paraguay and Pakistan. GM crops were initially introduced in South Africa in 1997 (Gouse, 2009), and currently GM crops (HT and Bt maize, cotton and soybean) cover 2.7 million hectares (James 2014). This can be compared with Burkina Faso, which is the next largest producer of GM crops in Africa, where Bt cotton was introduced in 2008 (Dowd-Uribe, 2014) and today covers 50000 ha (James, 2014).

tolerating local efforts to breed the Bt trait into local varieties, making the technology more affordable and better adapted to local agroecologies (Lalitha et al., 2009; Herring, 2007; Shah, 2008). It has also been shown that the local breeding of commercialised Bt cotton varieties in India placed pressure on the seed industry to introduce the Bt trait into locally suitable varieties (Lalitha et al., 2009). This indicates that it is possible to make GM crop technology part of a different technological trajectory, in effect making the technology more scale-neutral. However, examples from both China and India also show that the greater sophistication and novelty of GM technology makes it more difficult for farmers to take control over the technology compared with traditional breeding techniques. When farmers cross purchased Bt cotton with local cotton varieties without the necessary equipment and knowledge, they have no way of knowing if the Bt trait has actually been transferred to the offspring or if sufficient levels of Bt proteins are expressed by the plant to provide pest protection. Both India and China now have severe problems with uncertified Bt cotton varieties on the market where the existence and efficiency of the Bt trait are unconfirmed (Ho et al., 2009; Lalitha et al., 2009; Van Zwanenberg et al., 2011). In addition, pest insects have developed resistance to Bt toxins in several countries where Bt crops are commonly grown, including India, South Africa, the US and China (Kruger et al., 2011; Zhang et al., 2012; Tabashnik et al., 2013). Low-dose exposure to Bt toxin resulting from uncontrolled crossing of Bt and non-Bt varieties might be one reason for this; another is a lack of compliance with new management practices developed to delay resistance (Tabashnik et al., 2013), which is partly an outcome of the lack of agricultural advice on GM crops. The uncontrolled development and spread of Bt cotton has thus to some extent backfired on farmers, who in effect risk crop losses due to resistant insects and low-quality seed (Stone, 2011, 2004; Ho et al., 2009).

Available GM crops have been found to be more knowledge intensive than conventional crop varieties. With HT crops, farmers must adapt their weeding practices and spraying regimes. To ensure efficient use of Bt crops, farmers must know the types of insects to which the crops are resistant, and if they use pesticides they must adapt their spraying regimes accordingly (Jacobson 2013). In many countries farmers planting Bt crops are also required to plant refugia, *i.e.* sub-areas of conventional hybrids within the Bt crop to provide a feeding ground for targeted insects. This prevents the build-up of insect resistance to the Bt protein (Bates et al., 2005). The need to learn about these new crop features and associated practices clearly does not fit well with the global trend of reduced government spending on agricultural advisory services. Indeed, examples from India, China, South Africa and Argentina show how the combination of increasing demands for information concerning the introduction of GM crops with low availability of agricultural advisory services to smallholders has resulted in misinformation on GM crops and a widespread lack of compliance with new management practices (Jacobson and Myhr, 2013; Stone, 2004; Assefa and Van Den Berg, 2009; Pemsl et al., 2005; Ho et al., 2009; Van Zwanenberg et al., 2011).

This section has described how the close relationship between crop technology and its industrial production system that developed with the advent of hybrid technology has been further tightened with the entry of GM technology. The comparatively large degree of control needed to ensure the function of GM technology makes it costly and has stimulated a concentration of power in the private seed sector. This has limited the options available to farmers and, in particular, undermined the usefulness of GM crops to resource-constrained smallholders. The failure of efforts to disconnect the technology from its industrial production system in India and China shows how tightly the technology is coupled with its industrial production system. This is not to say that it is impossible to develop GM crops suited for smallholders and their more heterogeneous environments but, as shown in the examples above, this kind of development demands significant commitment and investment in technology development and advisory services targeted at smallholders. Talking about GM crops as scale neutral in effect conceals this need for significant political and economic commitment to making the technology work for smallholders.

6. Conclusions

This paper describes how the crop technologies used and the political and economic environment have both changed since the Asian GR, in ways that are not favourable for smallholder farming. Governments today spend less on support to agriculture, including agricultural advice, and the corporate shaping of crop technology research and development has significantly shifted the technological trajectory away from smallholders. This corporate control of crop technology and the shift away from smallholders' needs and interests have been strengthened by biological factors inherent in the crop technologies promoted as key drivers in the transformation of African smallholder agriculture today. In hybrid technology and the more recent GM technology, a highly controlled development process is needed to ensure the functioning of the technology. By virtue of their biological functions, hybrid crops and, even more so, GM crops thus facilitate corporate control over technology. This is not to say that the relationships are fixed, but it indicates that significant political and economic commitment is needed if new crop technology is to be of benefit to African smallholders.

Analysis of the factors that were central for the empirically observed scale neutrality of crop technology during the Asian GR shows that all these factors act in different ways today than during the Asian GR. As a result, it has become more difficult for smallholders in Africa and elsewhere to benefit from crop technology:

- many African countries today do not have the same access to cheap labour as was the case in many parts of Asia during the GR (Hull, 2014; White, 2012) (*i.e.* labour-intensive technology does not necessarily favour smallholders)
- financial and advisory support was central for observed crop scale-neutrality during the Asian GR (Feder et al., 1985). Today the trend is a reduction of government spending on agriculture in Africa and globally (FAO, 2016), which increases the financial risk for smallholders
- financial risk is increased further by the fact that seed is much more expensive today than during the Asian GR (Bonny, 2014). In addition, farmers are now seldom allowed to share and recycle seed (Netnou-Nkoana et al., 2015). This applies to most seed, but in particular to the seed of GM crops
- while government spending on advisory services has generally been reduced since the Asian GR (Tripp, 2001; Stone, 2004), GM crops increase subjective risk compared with conventional crops, as it is more difficult for farmers to learn about how GM crops work (Jacobson, 2013; Jacobson and Myhr, 2013)
- corporate control over crop technology increasingly directs crop R&D to serving large-scale, capital-intensive farmers (Parfitt, 2013). Fewer crop varieties are thus being developed for marginal environments (Jacobson, 2013). At the same time the effects of climate change are predicted to be particularly severe in parts of Africa (Boko et al., 2007), meaning that we will need crop varieties that can grow in such increasingly marginal environments.

In summary, this paper provides support for the idea that referring to crop technology as inherently scale neutral depoliticises the issue in a way that undermines, rather than supports, African smallholders in their need for crop technology adapted to their practices and contexts. It also indicates that, in order to support smallholder agriculture, it might be more effective to target the policy structure, which currently in many respects disfavours smallholders, than to focus on technological development within the current policy context.

From a theoretical perspective, this paper suggests that crop technological trajectories are significantly shaped by political, biological and agroecological factors. It also shows how these factors interact and produce outcomes that cannot be fully understood if they are studied in isolation. Combining insights from FSR with SST is therefore valuable in analysing biologically embedded farm technology such as crops. Without the systemic (agroecological) perspective on crop technology development provided by FSR, the co-shaping of crop biology, environment and technology development, which currently reinforces the strength of dominant market interests and disadvantages smallholders, would have been difficult to discern.

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