Building the new international science of the agriculture–food–water–environment Nexus in China and the world

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Abstract. The multiple, complex and systemic problems of the agriculture–food–water–environment nexus ("Nexus") are among the most significant challenges of the 21st century. China is a key site for Nexus research amidst profound socio-environmental problems. The policy implications of these problems have been authoritatively summarized elsewhere. This study presents discussions at an international workshop in Guangzhou that asked instead "What science is needed to deliver the growing policy commitments regarding these challenges? And, What changes are needed to the science itself?" Understanding and effective intervention regarding the Nexus calls for a paradigm shift: to a new kind of science of (capacity for) international, interdisciplinary, and impactful research working with and within complex socio-natural systems. We here argue that science must become proactive in approach, striving only for "minimal harm" not "silver bullet" solutions, and adopting an explicitly long-term strategic perspective. Together, these arguments lead to calls for reorienting science and science policy in three ways: from short-term remediation to longer-term optimization; from a focus on environmental threats to one on the opportunities for international collaborative learning; and toward supporting new forms of scientific career. We bring these points together by recommending a new form of scientific institution: a global network of collaborative Nexus Centres, under the umbrella of a global Food Nexus Organization akin to those of the human genome and proteome.

Key words: *agriculture–food–water–environment Nexus; China; complex systems; food security; international collaboration; new science.*

Citation: Zhu, X.-G., M. Parry, Y. Lu, M. Heard, G. Ying, S. Vaughan, J. Shen, A. Jenkins, Y. Wang, S. Lacorte, T. Ouyang, F. P. Salcedo, J. Niu, J. Quinton, C. Luo, F. Zhang, G. Zhang, W. Davies, K. Jones, and D. Tyfield. 2016. Building the new international science of the agriculture–food–water–environment Nexus in China and the world. Ecosystem Health and Sustainability 2(11):e01249. 10.1002/ehs2.1249

Introduction

This article summarizes discussion at a two-day workshop, hosted by the EuropeAid-funded SEW-REAP project, to take forward the scientific agenda regarding the agriculture–food–water–environment nexus (hereafter "Nexus"), with a particular focus on China.[12] Specifically, we focus on how science itself must be reframed in response to these challenges. First we discuss necessary

Manuscript received 23 May 2016; revised 17 October 2016; accepted 21 October 2016.
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[12] On 9th and 10th January 2016, approximately 40 leading scholars from China and the EU met at the International Research and Innovation Centre for the Environment (I-RICE), based at the Chinese Academy of Science's Guangzhou Institute of Geochemistry (GIG-CAS), Guangzhou, China. We gratefully acknowledge the funding of the European Union (ECRIP 348-010) for this event.

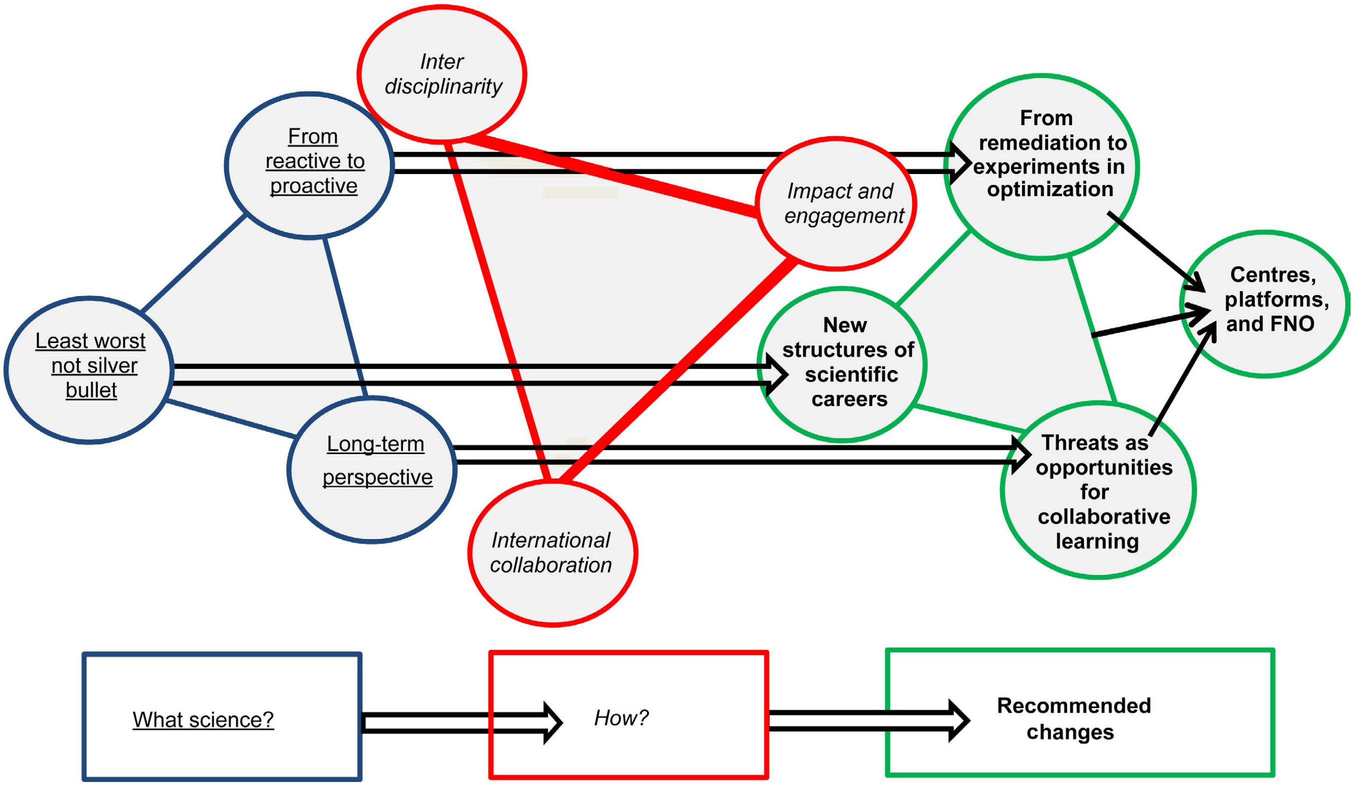

Fig. 1. Toward a new science of the Nexus.

changes to the substance and framing of a science of the Nexus, then changes to the process of science, before pulling these together in a set of three reorientations and one concrete institutional recommendation (see Fig. 1).

The multiple, complex, and systemic problems of the agriculture–food–water–environment Nexus are among the most significant challenges of the 21st century. The social, environmental, and economic implications of system failure within this Nexus affect all territories and globalized society as a whole. Over recent decades, however, the push to increase food production in China, together with population growth, economic development, land-use change, and climate change, has diminished ecosystem health and produced pollution that threatens future food production. Given the intensity of these existing socio-environmental challenges, China is a crucible for Nexus research.

Important issues in China include the following: water scarcity and quality (Khan et al. 2009, Li 2010); a "high-input, high-output" model of agriculture generating over-use of N-based fertilizers and pesticides (Ju et al. 2009, Shen et al. 2013, Zhang et al. 2013) and soil pollution, particularly from heavy metals (Gale and Hu 2012, Lu et al. 2015*b*, Wang et al. 2012, Ministry of Environment Protection and Ministry of Land Resources of the People's Republic of China 2014); biodiversity loss (Christopher and Tilman 2008), greenhouse gas emissions and climate change (Davidson 2009); and land and freshwater degradation (Guo et al. 2010).

These issues are often interrelated and present diverse and geographically specific environmental challenges, often exacerbated by current agricultural systems and practices. The challenges are compounded by overlaps with other key issues, including sustainable and equitable energy security (Pretty et al. 2002, Chen et al. 2006), access to mineral and other key resources (Shen et al. 2005, Miao et al. 2010), and waste and recycling (Troschinetz and Mihelcic 2009). China's agriculture is concentrated in regions that are water-stressed, leading to extensive irrigation with poorly treated wastewater (Huang and Wang 2009, Lu et al. 2015*b*). Increased urbanization, socio-economic trends to more meat- and dairy-intensive diets (Foley et al. 2011, Tilman et al. 2011), and a potential doubling of global food demand by 2050 compound the challenges. Sustainable intensification to agricultural production that is resource efficient and has a modest ecological footprint is thus a huge challenge in China (Shen et al. 2013, Zhang et al. 2013, Chen et al. 2014).

Many of these issues are well documented, including agreement on broad policy recommendations (Zhang et al. 2013, Li et al. 2014, Lu et al. 2015*a*, *b*). Policy in China, including science policy, has also recently demonstrated a shift toward an ecologically attentive perspective, including significant programs of integrated research. Indeed, realigning Chinese policy priorities around the top-level discourse of "ecological civilization" could be one of the most significant global opportunities to push forward an agenda for Nexus science (Sutherland et al. 2016).

There remain, however, considerable gaps in the science and scientific institutions required to underpin effective decision-making and to improve significantly China's agriculture and environmental management. Here, we highlight the next steps needed to develop an integrated research program to inform and direct China's (and thence global) long-term environmental sustainability and food security (Lu et al. 2015*a*).

Elements of a Necessary Paradigm Shift

"What science?" The substance of the science of the Nexus

Three key conclusions emerged from discussion regarding a science that takes seriously the system complexity of Nexus issues.

From reactive to proactive

It is no longer enough for Nexus research and policy to be primarily reactive, limited to fire-fighting the latest urgent challenge or responding to short-term funding opportunities and priorities. Instead, a proactive approach of complex system governance for the longer-term is needed (Lu et al. 2015*b*), treating "food production… *as part of* an environmental system (soil, air, water, and biodiversity) and not independent from it" (Lu et al. 2015*a*, emphasis added).

This shift will not be possible without profoundly rethinking how to address these Nexus challenges, or else attempting to grasp systemic complexity will simply add more demands to an already-insupportable burden. Dealing with urgent problems is currently stretching both the scientific enterprise and political process to their limits, before we add the imperative of shaping of broader systems. However, the latter ambition must be accepted as the necessary starting point given the irreducible complexity and interconnectedness of the challenges themselves. Moreover, embracing this paradigm shift reveals two key ways in which tackling the grander, systemic challenges becomes feasible once they have been thus reconceived.

"Minimal harm" not silver bullets

First, to grapple with these complex systemic challenges we must strategically concede that only piecemeal and incremental solutions to many existing urgent problems are possible. This admission more properly adjusts the expectation of what can be achieved, affording a more pragmatic and viable approach instead. For instance, the challenge of cleaning up China's polluted soils is a task so large (Hornby 2015) that it is self-defeating to begin tackling it on the premise that it can be done quickly, neatly, and affordably given current socio-technical, scientific, and economic conditions.

Instead, the challenge is to tackle such problems as a process and to accept the necessity of short-term wins within a longer-term strategic research framework that, given the complexity and specificity of the challenges, does not even aspire to "silver bullets" or the single right answer. Along the way, trade-offs in such work will also be many. This includes choices regarding where to focus research, data accuracy at particular scales of analysis, and issues of data uncertainty when data are integrated across scales and/or extrapolated to other geographical, social, or ecological contexts.

This is a process, therefore, that aims for a Hippocratic approach of minimal harm or "least worst" ways forward. What counts as the "least worst" will then itself develop over time and, one hopes, improve. In particular, this process will likely unfold through cumulative scientific learning about complex systems (which has only just begun) alongside socio-technical changes, such as shifts from linear to more circular economies and changing practices and expectations. The goal, thus, is for these parallel processes of learning about complex systems and transforming them in practice to feed each other toward the realization of beneficial system changes that cannot be planned in advance.

A long-term perspective

Secondly, a paradigm shift in Nexus research demands adoption of a longer-term perspective. Growing understanding of complex systems increasingly reveals the possibilities of accurate prediction to be slight indeed (Wilkinson et al. 2013). Yet adopting a longer-term perspective and learning how to do this forecasting better remains possible and crucial insofar as two points are acknowledged that: Dealing with these Nexus challenges is *per se* a long-term project (as just discussed) and many important changes, both positive and negative, may take decades to manifest (e.g., Sebilo et al. 2013).

Moreover, only attention to the long-term evolution of relevant systems offers any hope of working toward solutions that do not generate other, possibly more alarming, ecological challenges for the future. Conversely, adopting a long-term perspective also opens up pragmatic possibilities that alleviate the insupportable demands for immediate improvement to the more manageable idiom of "more haste, less speed" or "欲速则不达" (*yusu ze bu da*—"haste makes waste").

"How?" The process of science

The doing of Nexus science must also be systematically transformed in regard to the "3 I's" of interdisciplinarity, international collaboration, and impact and engagement.

Interdisciplinarity

The complex and multi-dimensional nature of Nexus issues—as well as the relevance and suitability of findings for subsequent impact (see 'Impact and Engagement')—places a particular demand upon interdisciplinary research across the natural and social sciences. The opportunities (and gains) that result from integrated systemic knowledge to assist policy and practice are likely to be considerable. Currently, however, there are insufficient mechanisms to support interdisciplinary research, even as it remains a significant challenge (Stirling 2016): communicating across different approaches, terminologies (including meanings of ostensibly similar terms), and tacit knowledge of disciplines demands concerted efforts. Novel forms of collaboration to facilitate the integration of disciplinary knowledge and data are thus needed.

For example, mathematical modeling could play a key role in Nexus research to improve agro-ecological systems management, but only if the significant challenges it raises are tackled. The science of the Nexus involves new challenges for modeling, such as optimizing contending forms of uncertainty and data integration at and across different scales. Regarding sustainable intensification confronted with water scarcity, for instance, field-scale or small-scale knowledge on biophysical or physiological processes and environment evolution can be collected. But incorporating them into macro-scale hydrological models and large-scale circulation models raises difficulties, both in terms of scale and data availability. These challenges are exacerbated by the need to integrate these small-scale processes as they are being affected by changing and uncertain background environments, such as the elevated carbon dioxide concentrations. But these contexts matter profoundly. For example, any given genetic drought-resistance trait in a plant can have positive, negative, or neutral effect on yield, depending on the drought scenario in the field.

Trade-offs and challenges are thus encountered at every stage and level of model development. Models must be directly linked to farmers' agronomic practices, while at the same time they must be computationally efficient and pragmatically achievable for large-scale optimization studies. Efforts to collect data related to the processes spanning different spatial and temporal scales are needed for model parameterization, validation, and establishing confidence intervals. But both practical limitations and judgement regarding prioritization are inescapable regarding what data are collected, no matter how systemic the ambitions.

These novel challenges, however, are also an opportunity. New collaborations could engender a paradigm shift in model-building research to enable development of truly integrative models that guide development of sustainable food–agriculture–water–environments. Developing such a complex model goes beyond the expertise of any single individual researcher, PI, or laboratory. Community joint efforts are required to realize such models. To date, most models are developed in different laboratories, coded in different computational languages, and documented in different levels of details, which makes model integration extremely difficult, if ever possible. To enable the models to be used and further improved by a large research community and thereby become a basis for a new Nexus science, common frameworks for model development, parameterization, integration, and comparison need to be developed urgently. This requires a change in the normal processes of model-building research, from the current scattered effort, in which individual laboratories are the unit of the model development, to a consortium or community-based model-building effort. A major community agreement for such a paradigm shift is needed now to develop such joint model platforms to support development of integrative agriculture–food–water–environment models.

International collaboration

These considerations lead directly to considering how the issues in question also place a premium upon international collaboration in Nexus-related research. This is not just a matter of maximizing the advance of relevant science and innovation by bringing together the best teams, wherever in the world they may be based, so as to have the biggest impacts on these global issues, wherever these may be made; crucial though this is. But, also, the greater importance of place-specific contexts in understanding and intervening in concrete agriculture–food–water–environment systems—given the diversity of climatic, geographical, ecological, and social settings around the world—paradoxically demands concerted cooperation in research and sharing of learning across these sites.

Yet, selecting, initiating, and funding such Nexus research is difficult at present and is also particularly exposed to the need to negotiate funding boundaries—political, geographical (at various scales, e.g., between city regions or internationally), and ministerial (e.g., with some 39 ministries involved in agricultural and environment issues in China). Currently, Nexus research needs funding from multiple scales but intergovernmental programs of joint projects are priorities, including China–EU through H2020, or China–UK through the Newton Fund. While such bilateral funding is growing, therefore, it remains unsystematic and unpredictable.

Impact and engagement

None of this research is possible or purposeful without end-user engagement and not just with policymakers. Connections with farmers, including smallholders, are especially important, taking into account their different capacities, levels of dependence on farming, levels of education, and experiences of farming, etc., in different regions. Such engagement must become an increasingly normal, expected, and adequately supported element of research in this field, so that the new Nexus science will form a complete cycle of research, development, and policy application. But the institutions to support the extra efforts and time involved in doing knowledge transfer (KT) successfully (Varner 2014) are generally lacking.

Yet, again, there is potentially significant positive impact if this engagement is done well. For instance, agronomic practices, whether recommended based on computational simulation studies or gained through experimental studies, can be tested in relatively small regions or by smallholders in millions of villages, building up practices of iterative and user-engaged learning that can also incorporate indigenous or bottom-up knowledge among farmers. Best practice can then be further expanded or tested through schemes and then promoted as policy to guide agriculture at national scale. For example, one such scheme is the science and technology backyard (STB) (Shen et al. 2013), already at 71 sites across China.

Moreover, lessons can be learned from other emerging systems sciences, such as genomics or proteomics. Here, the support from their respective global organizations and projects (such as the Human Genomics Organization (HUGO) and the Human Genome Project (HGP)) have proven invaluable in both support for KT and the concomitant strengthening of these emergent fields of enquiry (Holmes et al. 2016).

Reorientations and Recommendations

What, then, should be done? We advocate the following three reorientations, which reflect the transformations in science that follow from each of the three points above concerning changes to the substance of science (See *"What science?" The substance of the science of the Nexus*) when mediated through the set of changes in its process (See *"How?" The process of science*). These then, in turn, come together in a single concrete recommendation (see Fig. 1).

Reorientation 1: from remediation to optimization

First, regarding a proactive approach, it is understandable that policy attention regarding Nexus issues is primarily devoted to tackling "clear and present dangers," especially since some of these are already intense, including in China. The considerations above, however, yield a shift in perspective that sees experiments in optimized ecological food systems as being the necessary context for an "all hands on deck" commitment to mitigating existing problems, not in tension with this goal. For instance, while issues such as soil pollution or water scarcity and quality must be tackled, the perspective advocated shows that ignoring longer-term and systemic questions while focusing on short-term mitigation may well simply lead to even greater challenges.

Incorporating remediation efforts within projects framed by this bigger picture could not only indirectly improve them but also lead to the more systemic reduction in pressures for the reproduction and growth of those problems in the first place. This posits, for instance, a research agenda on optimizing systemic issues of Nexus *quality* (in its broadest sense) not just food quantity. This would include an early focus on closing existing gaps in yield efficiency across locations, rather than absolute yield maximization. It would also involve development and sharing of integrated programs of agro-ecological management and practices, such as integrated crop-soil system management (Chen et al. 2014) or integrated pest management (FAO 2010), which already show benefits but have room for further improvement. Such initiatives also may not be highly technological and/or expensive, even as new technologies may well have a significant role to play in the longer term.

Reorientation 2: from environmental threats to opportunities for collaborative learning

Secondly, from a long-term strategic perspective, the particular intensity of Nexus challenges in China should be viewed not just as a problem and threat in itself, but as a productive stimulus for a renewed commitment and a reshaped, more productive approach to international collaboration. For, with Nexus challenges confronting all regions of the world, there is a genuinely level-playing field between partners in terms of common ignorance, at present, about what (multiple, locally relevant) models of sustainable food systems would look like. Humanity together is still figuring out how to achieve the food, energy, and environmental sustainability within the boundaries of our planet Earth (Steffen et al. 2015). The opportunity and imperative for international collaboration thus becomes one of concentrated shared learning, monitoring, and data collection that may then, in turn, be applied in diverse national and regional contexts by those best-versed in their particularities. From such a long-term perspective, both China and its research partners (and all other countries besides) will gain tremendously from such joint efforts.

Today, by contrast, international collaboration between the EU and China, say, is often motivated by ideas of EU science as purveyor of solutions to China. This framing argues that the EU experience in the latter half of the twentieth century largely solved many of the Nexus problems now confronting China, albeit with just some unintended side effects that now need to be addressed. This sanguine picture, however, ignores both how many of the current Nexus challenges facing the EU emerged out of the very *successes* of earlier initiatives and policies (Beck 1992); and that what may superficially appear familiar problems in China to those previously encountered in the West are actually much more complex (Han and Shim 2010), not least because the former "solutions" of the latter did not take the Nexus into account.

Moreover, from the systemic, long-term perspective here, it is clear that this understanding of the mutual benefit from EU–China collaborations serves neither EU nor Chinese research partners well; nor, therefore, their collaboration. Instead, it traps both sides in a framework that must tend not to address Nexus challenges since their essential novelty is denied precisely by framing the supposed mutual benefit of collaboration on those terms of "experienced leader" and "follower." Far better to acknowledge that the EU history reveals not only solutions ready for transfer but also considerable experience about problems that should be forestalled, and all within a new, broader common challenge of tackling Nexus complexity.

Framed in this way, then, the intensity of Nexus issues in China is no longer just a problem. Instead, it is a positive stimulus and opportunity to overcome definitively an unhelpful but widespread assumption, namely that the paradigms of environmental policy and management in more developed countries do not themselves need to be similarly reframed within a novel systemic perspective. This policy change, in turn, could then be harnessed to motivate and reinforce the necessary paradigm shift in internationally collaborative Nexus research on a global scale.

Reorientation 3: new structures of scientific careers

Finally, regarding a "minimal harm" approach, the crucial contribution to human knowledge of engaged, complex-systems work must be acknowledged even where the universal applicability of findings concerning Nexus issues in specific and diverse locations will be significantly more qualified than that of basic research. To the contrary, at this stage in the evolution of our understanding of these complex systems, more generalizable and universal understanding can only be hoped to emerge—in due course—through the pooling of massive databases of such self-consciously contextualized case studies. It serves no one, including the advance of science itself, to belittle highly localized and deeply engaged work in favor of more familiar research approaches in these early stages of collation of such knowledge. Rather it only slows the possible emergence of such meta-level insights, including by making such work difficult and unattractive, especially for promising and ambitious early-career scientists.

As such, new forms of publication and scientific credit must evolve. These new career structures must acknowledge and reward new paradigms and emerging standards of high-quality complex-systems research that is working with the complex systems it is studying. These should be not replaced but be on top of and alongside existing familiar systems that reward advances in "blue sky" or basic research through citation, research funding and prizes, or technological advance through commercial success.

Centres, platforms, and a "FNO"

These three key reorientations point to the key challenge for Nexus science and the focus of our one concrete recommendation: the need for new scientific institutions. In particular, global networks of Centres and Platforms, in China but also across the world, emerge as key new scientific institutions, perhaps unified under a global Food Nexus Organization (FNO) and/or Food Nexus Project (FNP) akin to those of the omics sciences mentioned above. These new Centres would not only be home to a platform that institutionally enables diverse research expertise to convene into fluid, bottom-up collaborations of mutual benefit to all involved. They could also manage the key issues of ongoing and "glocal" engagement with stakeholders (e.g., farmers) with the necessary resources to do this well, with rewarding scientific careers, and provide bases for the development and propagation of solutions relevant to different places and contexts, a process that is necessarily active and collaborative (including with stakeholders), not just one of passive diffusion of a single, international best practice.

Such Centres could also harbor modeling hubs, with which model comparison, integration, parameterization, and prediction on specific issues could be realized and in which the inescapably particular and detailed practical challenges facing interdisciplinary and international collaborative work could be actively supported and worked through, in an ongoing process of deepening the new Nexus science. As single physical locations and institutions, this modeling work could also then be supported, for instance, through a super-computing facility or cloud-computing environments. And as an integrated model emerged across the network and the FNO, the Centres could provide crucial support to enable a proactive approach toward KT that develops a new standard of sustainable food–water–ecosystem governance.

In this capacity, Centres also could then act as hubs (at different relevant geographical scales) to house and cultivate new institutions of environmental monitoring; and where this involves not just themselves as collectors of data but also local stakeholders, so that these actors may too become (over the coming decades) key sources of data collection, sharing, and system governance. The long-term goal of Centres, thus, is to become a key node in a dispersed global network (under a FNO) for generation and sharing of sustainable food practices and knowledge: the new science of the Nexus. To be sure, this discussion leaves much practical detail still to be worked out. But international joint funding calls dedicated to Nexus science, the establishment of a global Food Nexus Organization to oversee and coordinate growth of this science, and novel forms of (international) funding for the Centres, at least for their initial establishment, are all crucial practical next steps.

Acknowledgments

We gratefully acknowledge the funding of the European Union EuropeAid for the SEW-REAP project (ECRIP 348-010) that has sponsored the work behind this article.

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