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Pathways for advancing pesticide policies

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Numerous pesticide policies have been introduced to mitigate the risks of pesticide use, but most have not been successful in reaching usage reduction goals. Here, we name key challenges for the reduction of environmental and health risks from agricultural pesticide use and develop a framework for improving current policies. We demonstrate the need for policies to encompass all actors in the food value chain. By adopting a multi-disciplinary approach, we suggest ten key steps to achieve a reduction in pesticide risks. We highlight how new technologies and regulatory frameworks can be implemented and aligned with all actors in food value chains. Finally, we discuss major trade-offs and areas of tension with other agricultural policy goals and propose a holistic approach to advancing pesticide policies.

Pest management in agricultural cropping systems is critical for food security[1] but the adverse effects of pesticides on human health and the environment have been repeatedly shown[2–4]. The reduction of potential risks from pesticide use is widely discussed amongst agricultural policy and food value chain actors worldwide[5–7]. Reduction measures range from the development of new technologies and agricultural inputs to the implementation of more sustainable farming systems and the introduction of food labels. All of these strategies are guided, monitored, and supported by public policies (Fig. 1).

Mixed success from policy efforts in Europe

Though risks from agricultural pesticide use are heterogeneous across global regions, Europe serves as a valuable case study for an assessment of policy design and instruments. It has a leading role in implementing pesticide policies and exports standards to interlinked global agriculture, sometimes also referred to as non-tariff trade barriers[8] —examples include food quality and safety standards, like maximum residue limits for pesticides on food, or the technical standard of Hazard Analysis and Critical Control Points[9,10]. Direct payments to farmers constitutes a substantial part of farm incomes in Europe and are tied to cross-compliance regulations and the provision of multiple ecosystem services.

European pesticide policies include regulatory frameworks, direct payments and, since 2011, mandatory National Action Plans to reduce risks and impacts of pesticide use on human health and the environment (Directive 2009/128/EC). Current assessment of pesticide active ingredients is based on hazards rather than the actual risk of exposure of humans and the environment to substances, which would require data collection and monitoring beyond current levels, as well as modelling of impacts on the scale of the whole agricultural system[11,12].

Despite substantial efforts in the last decade, there is little evidence that Europe has achieved the reduction in pesticide risks and impacts as mandated in National Action Plans. A direct assessment of policy targets proves difficult, as most European countries do not publish or monitor data on risks — or environmental and health impacts of utilized pesticides on a national level — which is a major weakness of current policies[13]. However, we know that since the introduction of National Action Plans pesticide sales in Europe have remained stable[14], farmers' usage has not decreased (as seen in France)[15] and surface and groundwater contamination still regularly exceed legal thresholds[4,16]. This suggests weak effects of current policies — in line with general public perception in Europe that current agricultural policy does not sufficiently consider the protection of the environment[17,18]. Pesticide policies need to be revised and advanced. Here, we take a multi-disciplinary view and outline current research that shows ten pathways to a successful reduction of potential risks from agricultural pesticide use.

Policy indicators, targets and design

Adjustment of the design of policies, their targets and indicators for measuring risk are required.

Tangible pesticide risk indicators. Specific and measurable targets are required to achieve a reduction of potential environmental and health risks from agricultural pesticide use[19]. Risks — and indicators to measure those risks — require definitions, which are missing in most European countries[20]. Purely quantitative indicators (that is, kilograms of active ingredients or number of standard dosages) are currently used for a posteriori risk assessment, but quantitative measures alone do not necessarily correspond with potential environmental and health risks. Policies focusing on quantity reductions could induce the use of low-dose pesticides with a higher efficacy on target organisms but at the same time a stronger (eco)-toxicological effect on non-target organisms[21]. Effective and efficient policies require national governments to prioritize country-specific reduction goals for potential environmental and health risks, set tangible indicators to quantify the specified potential risks and transparently monitor and publish data on these risks at a national level. New sensor and monitoring technologies increasingly allow the implementation of cheaper, real-time risk-monitoring systems over time and space[22,23]. Denmark demonstrates that spatially explicit and risk-oriented indicators can

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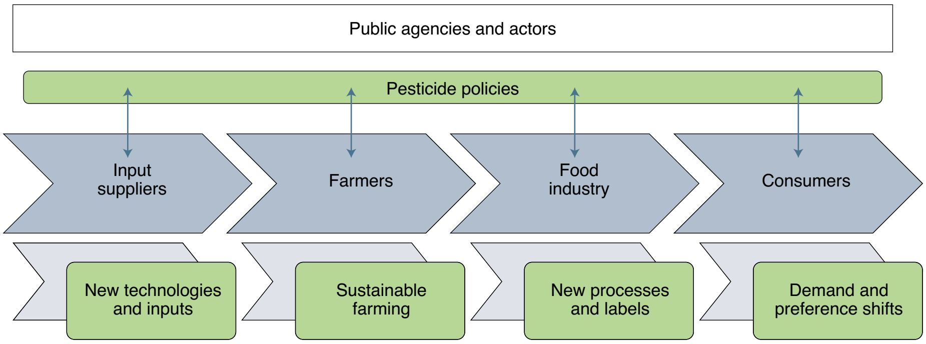

Fig. 1 | Interactions between food value chain actors and pesticide policies. Pesticide policies interact with input suppliers, farmers, the food industry and consumers — each actor can contribute towards sustainable food systems with actions specific to their role (bottom row). Current policy measures can be classified as command and control measures (for example, pesticide authorization, bans and use regulations), market-based measures (for example, pesticide taxes, financial support of new technologies and direct payments) and information-based measures (for example, education, labelling and awareness raising). Many specific, national or regional measures are contained in each of the three categories and may target conflicting policy goals[78].

help to establish successful policies, which achieve a reduction in pesticide load[24].

Dimensions of policy targets. Policies typically focus on intensive margins, that is, potential risks of specific crops or products, such as the ban of neonicotinoids[25]. However, pesticide use is highly heterogeneous across crops and different agricultural systems[15,26]. Policy-induced changes in farmers' land use through extensive margins, such as the switch from one crop to another, or super-extensive changes, like switching from conventional to organic farming, have large effects on use levels. Extensive and super-extensive margin effects may even point in the opposite direction of intensive margin effects. For example, a subsidized insurance may induce reductions in use levels per hectare, but lead to an expansion of economically more risky crops that are often more pesticide intensive[27]. Therefore, it is crucial for policies to consider intensive, extensive and super-extensive margins in the design and evaluation of policy measures (see section 'A holistic approach to pesticide policies'), allowing for long-term implications of policies regarding land and technology use. Critical discussions are required about targets for pesticide use levels and more sustainable land use and agricultural systems at a regional and landscape level[28,29].

Realignment of agricultural policy goals. European agricultural policies aim to enable multiple ecosystem services and to be aligned with the United Nations Sustainable Development Goals[28,30], but stricter pesticide policies could have unintended side-effects on other policy goals, and vice versa[18]. For example, they might induce changes in land use and management practices that could decrease food production and quality, increase soil erosion or lead to higher greenhouse-gas emissions[26]. Banning specific pesticides might even foster the use of more harmful ones[31]. Resistance management is key in this regard: banning currently registered compounds, while only slowly marketing new, lower-risk active ingredients, makes alternation of active ingredients impossible in the long-run. Unintended side-effects of policy measures need to be clearly acknowledged and quantified by all actors; policy measures that reduce trade-offs have to be prioritized. Market-based policy instruments, such as taxes, are particularly suited to incorporate external costs and trade-offs into decisions made by farmers, the food industry and consumers. Long-term vision and commitments to policies are needed to foster investments and the development of efficient strategies. Moreover, to gain momentum, strong and persistent policy signals to the actors in the food value chain are needed. A good example is the successful establishment of a large-scale cereal production programme with highly reduced pesticide use over the last 30 years in Switzerland, which is based on an interplay of governmental direct payments, a market-based price mark-up and labelling to consumers[26].

Farmer and consumer actions

The behaviour of farmers and consumers is key for future policy success.

Farmer decision-making processes. Although all actors in the food chain are involved in the reduction of potential pesticide risks, crucial pest management decisions are made at farm level[32]. Pest development and weather conditions are processes with major stochasticity, leading to uncertainties in crop growth and efficiency of pesticides[33]. Risk perception and preferences of farmers — and information about uncertainties — influence their evaluation of pest management costs and gains so that they may not follow a strictly profit-maximizing rationale[34]. Further, behavioural factors, such as perception biases and habits, influence the farmers' decision-making[35,36]. Effective policies must consider farmers' heterogeneous behaviour and decision rationales[37] regarding pesticide applications and offer differentiated policy solutions. For example, insurance reducing uncertainty for very risk-averse farmers[27,38], pesticide taxes or incentives driving shifts in economic behaviour[39], or more information and extension services targeting farmers who lack information on alternatives may work best in achieving policy targets[38], respectively. Importantly, farmers' self-selection allows policy-makers to reduce the complexity and specificity of well-designed polices — and may increase cost-efficiency. For example, imposing a tax will ensure that those with the lowest marginal abatement costs reduce risks, while those with higher abatement costs, such as producers of high-value crops, do not.

Consumer choices and preferences. Consumers commonly rely on simplistic assumptions when evaluating the risks of chemicals[40] — the natural-is-better[41] and contagion heuristics, where laypeople ignore the quantity and focus on the act of contamination[42], may be especially important in the context of pesticides. Public chemophobia persists and citizens are generally concerned with pesticide use[40], yet present a strong insensitivity to dose–response relationships[43]. Demand for foods produced with reduced amounts of pesticides may be limited because such labelling would remind consumers of undesirable chemicals used in their foods' production — consumers commonly value labels of organic crops produced without synthetic pesticides higher than labels indicating reduced use[44]. In contrast, free-from labels appear to create biased perceptions because consumers can wrongly conclude that goods without such a label may be less healthy, which is not necessarily the case[45]. Price signals (for example, incorporating external costs of pesticides) in combination with information have the potential to drive consumer behaviour and policies that alter agricultural practices and systems. However, these systems must still produce food products that fulfil consumers' preferences.

Sustainable plant protection

Policies need to enable sustainable plant protection.

Pesticide admissions and regulations. Despite admission of new pesticides to the European market being strongly regulated and following the precautionary principle, new evidence on adverse effects are found and dozens of formerly registered pesticides are now restricted or banned[46]. Simultaneously, fewer new active ingredients are authorized[47]. Admission re-assessments focus on individual active substances and are governed by their current authorization expiration date, rather than adopting a holistic, long-term strategy. For residue levels, retailers creating stricter private standards does not necessarily lead to safer products but might increase the risk of gaps in plant protection measures and pest resistances.

Development and registration of new and safe pesticides requires improvements to the admission process. In the pre-authorization phase, creation of a single authority for handling active ingredient authorization and monitoring would improve coordination and unify the authorization process. Instead of relying on industry-supplied data, more assessments by anonymous, accredited laboratories would increase credibility and trustworthiness whilst reducing conflicts of interest. Environmental parameters should be used to assess potential risks from transformation products. Registrations limited to safer, more efficient products would enable faster post-authorization risk assessment, whilst shorter time periods between market release and risk investigation by public bodies would improve the authorization process[48].

Currently, risk assessments only focus on single pesticides and single crops — a more holistic view of risk assessments on the landscape level is needed to assess real-world pesticide use[11]. Agreed definitions of low-risk products in fast-track authorization systems with lower data requirements and long-term authorization periods are required to enable farmers to replace banned, toxic pesticides with products containing less harmful active ingredients, whilst simultaneously maintaining effective resistance management. A dynamic policy framework would support pesticide vigilance in all European countries[49] — such programmes have already been established in Denmark[50] and are being implemented in France[51].

Sustainable farming systems. Sustainable agricultural systems can potentially decrease agricultural pesticide use[29,52,53] following the efficiency–substitution–redesign framework[29] — optimizing (for example, precision farming), substituting (for example, biocontrol agents or mechanical weed control) and redesigning (in) the current cropping system (for example, favouring biotic interactions). In Europe, cross-compliance regulations comprise aspects of integrated pest management, with farmers receiving direct payments for conversion to extensive or organic production systems. Despite their potential[54], tools like prevention and non-chemical pest management are not widely considered by farmers due to the knowledge-intensive nature of these systems, the higher risks and potential differences in efficiency, which can result in higher short-term costs than conventional practices[3]. Economic incentives encouraging farmers' adoption of agro-ecological and integrated pest management measures have to account for the farmers' decision rationales and require the support of official and independent advisory services. Current plans for the reform of the Common Agricultural Policy are only addressing these issues indirectly[28], missing a golden opportunity to promote pesticide-free farming systems.

Plant breeding strategies. For centuries, resistance breeding has contributed to crop productivity and plant disease management[55], and will continue to be a basic requirement for mitigating potential pesticide risks in Europe. However, plant breeding is a long and complex process, which is often unable to keep pace with the rapid evolution of pathogens or the emergence of new pests — processes that are increasingly driven by globalization and climate change[56,57]. Genomics and new plant breeding techniques provide enormous potential to increase the speed and technical opportunities in the development of resistant cultivars[58]. Current examples include the deployment of resistance sources from wild crop relatives that were lost during domestication[59] and the specific modification of resistance genes to increase their effect spectrum or to make them more durable[60]. However, the link between the value of advanced plant breeding and the reduction of pesticide use is often neglected in public discussions across Europe.

Regulators face challenges in balancing the benefits of new breeding technologies with potential risks, costs and lack of political support[61]. In the case of genetically modified crops — which have been widely utilized around the globe — strong regulations in Europe, such as restrictions on the co-existence of genetically modified and conventional crops, have hindered wide-spread adoption[62,63]. Despite benefits in pesticide reduction[64], negative consumer perception of genetically modified crops and knowledge gaps on plant breeding techniques in wider society have maintained a regulatory framework that prohibits the use of the latest gene technology developments. Europe can benefit from technologies like CRISPR–Cas to achieve durable resistance efficiently or provide easy access to resistance sources and crop diversity in gene banks (EU Council Decision L293/103) — these tools can strengthen plant breeding and take advantage of the enormous potential genetic diversity for crop improvement[65]. Thus, European policies require a revision of gene technology regulation in a differentiated, scientifically justified[66] and practically implementable manner[67].

Smart farming. Information and communication technologies will disrupt agricultural practices to potentially reduce agriculture's ecological footprint[68]. Artificial intelligence, for example, can aid detection and classification of weeds, pests and diseases precisely and efficiently; images taken from unmanned aerial vehicles or from tractor-mounted spraying booms allow targeted spraying, decreasing applied pesticide quantities. Challenges still remain: occlusion by other leaves or reflective leaf properties can hinder detection[69] and current or future precision farming technologies are currently mainly profitable for larger farms, for example, due to economies of scale[70]. Nevertheless, large-scale, rapid adoption will likely occur once these technologies have proven their value in the field, especially through push and pull mechanisms like combining agri-environmental policy instruments such as taxes and subsidies[39,70]. Finally, investments in technical infrastructure, such as access to high-speed internet connections, satellite images, data platforms — and the development of suitable legal frameworks — are essential for enabling widespread adoption of these technologies.

Efficient and dynamic pesticide policy portfolio. Based on policy from water use and climate change mitigation, the most effective and politically feasible way to reduce potential risks consists of creating a policy mix of source-directed and end-of-pipe solutions[71,72]. Source-directed measures, such as taxes on pesticides and carbon emissions or energy, require considerable behavioural change from the target group and are often hindered by political

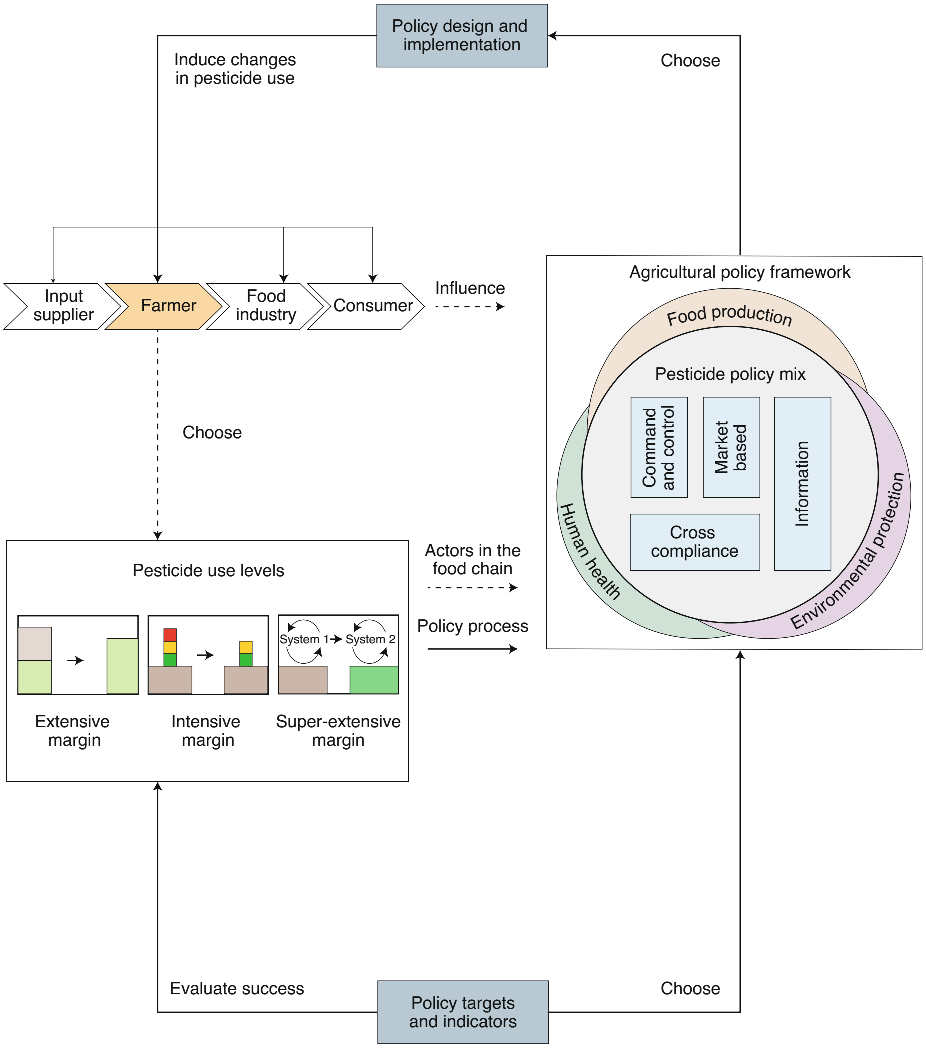

Fig. 2 | A holistic approach to pesticide policies. Policy targets and indicators (bottom) feed into the choice of the pesticide policy mix (right), which has to account for interactions between food production, human health and environmental protection — and is embedded in the agricultural policy framework. Design and implementation of policies are essential for their effects on actors (top) — and ultimately for farmers' choice of pesticide use levels (left). Success of policies may be evaluated along extensive, intensive and super-extensive margins, which refer to changes in pesticide use levels induced by farmers' land use changes, changes in pesticide use intensity (for example, per crop or hectare) and changes in the agricultural system (for example, switch from conventional to organic agriculture), using the defined policy indicators and targets.

opposition[61]. End-of-pipe measures, such as filtering or treatment of wastewater, reduce pollution exposure through technical solutions, which are effective but costly. Effective portfolios require so-called creative destruction, where contradictory policy instruments are replaced with new ones and are based on the nature of problems rather than political power games[73]. Thus, policy instruments should account for the complex nature of risk reduction and connect different sectors, decisional levels, and jurisdictional areas[74] (see section 'A holistic approach to pesticide policies') — an example could be reinvesting revenues from pesticide taxes (incentivizing changes in individual, application-specific behaviour) in the promotion of sustainable farming systems, leading to sector-wide support to switch to alternative crop protection techniques[39]. Policies must dynamically adjust to future challenges in pest management, such as changes in pest pressure (for example, through climate change and invasive species)[57,75], trade-offs in new agricultural systems or increasing evidence on residues and pollution[23]. This requires the definition of potential policy pathways in response to key challenges — and a monitoring system that can trigger policy actions[76].

A holistic approach to pesticide policies

One decade of major pesticide policy efforts has demonstrated that current polices are not effective in reaching their risk reduction goals. Here, we have shown that pesticide policy is bigger than the admission and regulation of single pesticides. Using a holistic framework (Fig. 2), we outline pathways for a successful reduction of potential risks from agricultural pesticide use without putting other ecosystems services of agriculture at risk.

Pesticide policies involve trade-offs and stress-points. Different actors within the food value chain may not perceive all reduction measures as equally promising. New technologies can reduce trade-offs in policies but may not be accepted by consumers. Farmers may not use more sustainable farming practices, new technologies or low-risk compounds if they are less profitable, more complicated and/or less effective than conventional approaches. Further, individual policy goals may contradict each other and lack reliable long-term planning horizons. Bans of single pesticides and diverging private standards for residues may, for example, increase long-term gaps in plant protection and lead to more resistances with severe agronomic consequences.

A new holistic and simple policy framework is needed to improve current pesticide policies. Creating simple, generic and long-term policy goals for all actors in the food value chain reduces policy complexity and maintains flexibility in policy tools and measures. The framework must be based on clear and tangible policy goals that include transparent assessment and monitoring procedures for risks — thus, enabling a transition from the current hazard-based system to a risk-based system. To overcome conflicting goals between food production, environmental protection, biodiversity and human health — and avoid single, isolated solutions for every policy goal and actor in the food value chain — pesticide policy should be integrated in a holistic food policy framework[77]. The political process must be dynamic and policies have to be continuously adapted to fit future changes in agricultural systems. The Farm to Fork Strategy, which is at the heart of the European Green Deal, and the upcoming agricultural policy reforms in Europe present an important opportunity to advance current policies — and to take a major step forward towards the reduction of potential risks from pesticide use.

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N.M. and R.F. conceived of and led the manuscript writing and editing. The final manuscript was based on written input from all authors. All authors carefully revised the manuscript and approved the submission.

Competing interests

The authors declare no competing interests.

Additional information

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