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DATA DRIVEN WEED MANAGEMENT: TRACKING HERBICIDE RESISTANCE AT THE LANDSCAPE SCALE

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I. INTRODUCTION

Limiting the prevalence of herbicide-resistant weeds requires consistent, data-driven management implementation along with accompanying policy and legal frameworks designed to mitigate common-pool-resource problems.[1] Although weed population dynamics operate at scales above farm-level, the emergent effect of neighboring management decisions on in-field weed densities and the spread of resistance traits in the landscape remains unclear. Further, the ability to empirically test these emergent outcomes is limited by socio-cultural and economic barriers and management heterogeneity that impede contiguous implementation across space.[2] There is well-supported agreement that large-scale implementation of diversified weed management is key to combating new weed invasions and the rise of herbicide resistance (HR).[3] However, extensive evidence suggests scientific recommendations are minimally implemented by stakeholders. This limitation widens a significant knowledge gap in our ability to evaluate or set long-term management targets. Moreover, existing regulatory approaches to weed management generally fail to address herbicide resistance at the landscape scale, and the increasingly diverse ownership and tenancy patterns in Midwestern farmland add to the complexity. An integrated, data-driven simulation model that predicts the spread of herbicide resistance traits, while

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1. *See* A. Bryan Endres & Lisa R. Schlessinger, *Legal Solutions to Wicked Problems in Agriculture: Public-Private Cooperative Weed Management Structures as a Sustainable Approach to Herbicide Resistance*, 3 TEX. A&M L. REV. 827, 829 (2016) (identifying herbicide resistance as a common-pool-resource problem).

2. *See infra* notes 56–59 and accompanying text (discussing social and economic barriers).

3. *See generally* Jason K. Norsworthy et al., *Reducing the Risks of Herbicide Resistance: Best Management Practices and Recommendations*, 60 WEED SCI. 31 (2012).

accounting for existing social and legal complexities, can help to slow the growth and prevalence of herbicide resistance in the agricultural context. In other words, the use of enhanced data on landowner behavior, ownership patterns, and weed biology could provide a new means to control noxious weeds at a lower cost and toxicity.

II. WEEDS AND HERBICIDE RESISTANCE

Overreliance on herbicides, as well as lack of herbicide diversity, imposes intense selection pressure on weed populations and has independently driven the rise of herbicide resistance across major crop production areas of the U.S.[4] "Herbicide resistance, defined as the inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal to the wild type,"[5] originates through rare genetic mutation events.[6] However, resistance can be enriched rapidly by natural selection through repeated exposure to the relevant herbicides that are dispersed by numerous mechanisms at different spatial scales.[7] Processes that operate beyond the field scale, but influence in-field weed prevalence, such as control of new infestations that reduces seed rain,[8] depletion of weed seedbanks,[9] and the hygiene of equipment or products that move seed and pollen among fields, would particularly benefit from aggregated efforts.[10] While selection and enrichment are fundamentally local processes, managing the spread of HR traits depends on our ability to reduce gene flow both within and between individual farms by reducing seed and pollen production and minimizing the transport of weed seeds.[11]

Unfortunately, regular integration of effective practices into annual weed management has been reduced, or only employed after severe weed infestations emerge, due to the overwhelming adoption of herbicide tolerant

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4. *See generally* R.G. Wilson et al., *Benchmark Study on Glyphosate-Resistant Cropping Systems in the United States. Part 4: Weed Management Practices and Effects on Weed Populations and Soil Seedbanks,* 67 PEST MGMT. SCI. 771 (2011); W. Vencill et al., *Herbicide Resistance: Toward an Understanding of Resistance Development and the Impact of Herbicide-Resistant Crops*, 60 WEED SCI. 2 (2012).

5. Vencill, *supra* note 4, at 3.

6. Marie Jasieniuk, Anita L. Brule-Babel & Ian N. Morrison, *The Evolution and Genetics of Herbicide Resistance in Weeds*, 44 WEED SCI. 176, 177 (1996).

7. *Id*. at 176.

8. A. Alignier & S. Petit, *Factors Shaping the Spatial Variation of Weed Communities Across a Landscape Mosaic*, 52 WEED RES. 402, 408 (2012).

9. *See generally* Adam S. Davis, *When Does it Make Sense to Target the Weed Seed Bank?*, 54 WEED SCI. 558 (2006) (discussing weed seedbanks).

10. Norsworthy, *supra* note 3, at 46.

11. *Id*. at 34–35.

cropping systems in the mid-1990s.[12] Weed scientists commonly recommend conservation tillage, control of late-emerging or residual weeds, crop rotation, and timing and application of herbicides with different chemical mechanisms of action (MOAs) as weed-control tactics to delay the spread of herbicide resistance.[13] Although herbicide-tolerant crops were designed to be implemented as highly-effective tools in a diverse weed-management framework, their adoption instead led farmers to invest in increasingly simplified weed-management systems, frequently relying on a single herbicide MOA (primarily glyphosate) over large areas and multiple growing seasons.[14] Wilson et al. (2011) found a majority of surveyed growers used glyphosate as the only herbicide for weed management, even though 98% of academic recommendations involve applying at least two herbicide active ingredients and MOAs.[15] Consequently, selection pressures on weed populations have intensified and homogenized over time at large spatial scales, eroding the effectiveness of individual management tools such as glyphosate.[16]

Additionally, farm-scale costs of herbicide resistance can be substantial. For instance, Lambert et al. (2017) estimated the post-resistance changes in weed-management costs ranged between \$85 and \$138 ha^{-1}, with average costs increasing by \$98 ha^{-1} following the establishment of herbicide-resistant weeds in cotton-production systems.[17]

Some important herbicide-resistance traits, on the other hand, have negligible fitness costs.[18] In these cases, the frequency of the resistance trait

12. Michael D. K. Owen, *Weed Resistance Development and Management in Herbicide-Tolerant Crops: Experiences from the USA,* 6 J. FÜR VERBRAUCHERSCHUTZ UND LEBENSMITTELSICHERHEIT (SUPPLEMENT 1) 85, 85 (2011); David A. Mortensen et al., *Navigating a Critical Juncture for Sustainable Weed Management,* 62 BIOSCIENCE 75, 75 (2012).

13. *See* Vencill, *supra* note 4, at 2; *see generally* Norsworthy, *supra* note 3.

14. Hugh J. Beckie & Linda M. Hall, *Genetically-Modified Herbicide-Resistant (GMHR) Crops a Two-Edged Sword? An Americas Perspective on Development and Effect on Weed Management,* 66 CROP PROTECTION 40, 40 (2014); Bryan A. Young, *Changes in Herbicide Use Patterns and Production Practices Resulting from Glyphosate-Resistant Crops*, 20 WEED TECH. 301, 301 (2006).

15. Wilson, *supra* note 4, at 771.

16. *See* Thomas C. Mueller et al., *Proactive Versus Reactive Management of Glyphosate-Resistant or-Tolerant Weeds 1*, 19 WEED TECH. 924, 924–25 (2005).

17. Dayton M. Lambert et al., *"Resistance Is Futile": Estimating the Costs of Managing Herbicide Resistance as a First-Order Markov Process and the Case of U.S. Upland Cotton Producers*, AGRIC. ECON. (2017) (estimating costs and noting that the efficacy of remedial practices will vary geographically, depending on the degree of establishment of herbicide-resistant genes in weed populations and management costs).

18. *See* Martin M. Vila-Ajub et al., *No Fitness Cost of Glyphosate Resistance Endowed by Massive EPSPS Gene Amplification in* Amaranthus palmeri, 239 PLANTA 793, 793 (2014). Traits that offer competitive or survival advantages under select circumstances are often burdened with metabolic tradeoffs or fitness penalties that reduce performance in other scenarios. For example, if a resistance trait required producing large quantities of enzymes to

will increase unidirectionally toward saturation in surviving weeds each time the relevant herbicide is used.[19] Because of this, the mixture and rotation strategies outlined above will not prevent this process, although they may serve to delay it if implemented frequently in the landscape. From an implementation perspective, it is critical to understand that management decisions in real agricultural landscapes are not assembled into contiguous blocks of fields or farms, because individual operators, along with for-hire pesticide applicators, may manage fields scattered across a larger area with diverse farmland ownership. The interspersal of non-contiguous management units affects the degree of exposure to gene flow that neighboring fields experience from surrounding weed populations. This spatial configuration may have important repercussions for the level of participation required for cooperative weed-management units to succeed. The industry should integrate large-scale data on potential spatial patterns of farmland management across a region into a simulation model of resistance spread. This would allow comparisons of the efficacies of different social and legal frameworks to affect the spatial distribution of implementation and evaluate the capacity for large-scale coordinated management structures to slow herbicide resistance.

III. CURRENT REGULATORY APPROACHES AND INCENTIVES TO CONTROL WEEDS

Laws regulating invasive plant species or noxious weeds vary widely in their scope, interpretation, and application. These laws were first enacted in the late 19th and early 20th centuries to protect agricultural interests from the spread of noxious weeds associated with changing land-use patterns.[20] More recent modifications to the multi-jurisdictional system of federal, state, and local regulations have incorporated a desire to protect the environment and its ecosystem functions.[21] The ecology of plant invasion and

detoxify an herbicide, the plant would have to divert resources that would otherwise be invested in growth or reproduction to manufacture them. In the absence of the herbicide, resistant plants that produced these enzymes unnecessarily would be disadvantaged and should have relatively lower reproductive output than susceptible plants that did not produce them, and the frequency of the resistance trait should decrease over time.

19. Hugh J. Beckie, *Herbicide-Resistant Weeds: Management Tactics and Practices*, 20 WEED TECH. 793, 802 (2006).

20. James S. Neal McCubbins et al., *Frayed Seams in the "Patchwork Quilt" of American Federalism: An Empirical Analysis of Invasive Plant Species Regulation*, 43 ENVT'L L. 35, 45–47 (2013).

21. *See* David M. Lodge & Kirstin Shrader-Frechette, *Nonindigenous Species: Ecological Explanation, Environmental Ethics, and Public Policy*, 17 CONSERVATION BIOLOGY 31, 36 (2003). Although not technically a regulatory mandate with an impact on private persons, two presidential executive orders have further highlighted the need to consider the impact of

spread of noxious weeds differs across soil types, climatic conditions, and natural predators[22] and thus avails itself to variability in regulatory scope across jurisdictions, with the majority of actions taking place at the state level against a relatively mild level of federal backstop for weeds with national implications.[23]

At the farm-level, weed regulation plays a minimal role. As discussed below, regulatory programs focus on restricting the introduction and movement of existing noxious weeds but have limited scope with respect to dictating on-farm prevention or eradication measures. Moreover, state-based liability, whether civil or common law, is difficult. Thus, on-farm actions related to weed management is a function of economics—balancing the negative impacts on crop yield with the short-term costs of treatment—rather than part of a broader strategy of control or eradication.

A. State Weed Laws

States regulate noxious weeds via an inadequate blacklist system in which specific plant species are restricted for sale or transportation within a particular jurisdiction.[24] More than 600 individual plant species are included on these state-level lists.[25] In an empirical evaluation of state noxious-weed regulations and a corresponding jurisdictional-specific literature review of plants considered to be invasive in that particular state, on average only 19.6% of known invasive plant species were actually subject to regulatory

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invasive species on the environment. President Clinton, in 1999, issued the original executive order, and President Obama, in December 2016, amended the order to incorporate "considerations of human and environmental health, climate change, technological innovation, and other emerging priorities into Federal efforts to address invasive species; and strengthens coordinated, cost-efficient Federal action." Exec. Order No. 13112, 64 Fed. Reg. 6183 (Feb. 3, 1999), available at https://www.gpo.gov/fdsys/pkg/FR-1999-02-08/pdf/99-3184.pdf; Exec. Order No. 13571; 81 Fed. Reg. 88609 (Dec. 5, 2016), available at https://www.federalregister.gov/documents/2016/12/08/2016-29519/safeguarding-the-nation-from-the-impacts-of-invasive-species; National Invasive Species Information Center, LAWS & REGULATIONS - EXECUTIVE ORDER 13112, USDA, https://www.invasivespeciesinfo.gov/laws/execorder.shtml (last visited July 8, 2017) (summarizing both executive orders).

22. U.S. DEP'T OF AGRIC., NAT'L INVASIVE SPECIES INFO. CTR., PLANTS, http://www.invasivespeciesinfo.gov/plants/main.shtml.

23. McCubbins et al., *supra* note 20, at 40.

24. Lauren D. Quinn et al., *Navigating the "Noxious" and "Invasive" Regulatory Landscape: Suggestions for Improved Regulatory Performance*, 63 BIOSCIENCE 125, 125 (2013). State noxious weed lists, however, are highly reactive and tend to prohibit species only after there has been significant damage to agricultural production or the environment. *Id*.

25. *Id.*

control by the state government.[26] The result is massive under-regulation of known noxious and invasive plants.[27]

The regulatory gap widens when one considers enforcement mechanisms or other incentives for the control of noxious weeds. Effective enforcement of state weed control laws on private property is negligible, and there generally is no *ex post* liability scheme for the spread of weeds onto adjacent private property.[28] Although state statutes may impose an affirmative duty on the part of landowners to destroy noxious weeds on their property, there is no corresponding provision for civil liability for any resulting damages if the weeds were to spread.[29] This parallels the common law's approach to weed invasion.

The common law has treated the spread of weeds—even those that were intentionally introduced—as a "natural condition," and thus outside the realm of strict liability[30] or even nuisance.[31] From a legal perspective, individual land holdings are treated as isolated islands, separated from neighboring property by some invisible barrier, while ecologically they are connected and highly interdependent.[32] Thus at the state level, the regulatory regime does not match ecological reality.

B. Federal Regulation of Noxious Weeds

In a federalist system of government that observes the principles of subsidiarity,[33] the regulation of invasive plants due to variability such as

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26. *Id*.

27. States also over-regulate some plant species that are not considered invasive by the scientific community. In other words, the blacklist of noxious weeds also included many plants without noxious characteristics. Quinn, *supra* note 24, at supplemental materials 2–4. McCubbins et al, explored this over and under-regulation of noxious weeds from a structure perspective and found no statistically significant difference between noxious weeds listings controlled by administrative agencies, legislative bodies or local government entities. All performed equally poorly in coverage of noxious weeds. McCubbins, *supra* note 20 at 58–60.

28. McCubbins et al., *supra* note 20, at 48.

29. *Id*.

30. Vance v. S. Kan. Ry. of Tex., 152 S.W. 743 (Tex. Civ. App. 1912). *But see*, Collins v. Barker, 688 N.W.2d 548, 552 (S.D. 2003) (noting that landowner may not be liable for natural spread of weeds to neighbor's property but allegations in the specific case went beyond what could be considered natural proliferation of weeds and thus could be a private nuisance).

31. *See* NEIL E. HARL, AGRICULTURAL LAW § 11.02, p. 11–15 (Matthew Bender & Co., Inc. 2010).

32. MICHAEL LIVINGSTON ET AL., USDA, ERR-184, THE ECONOMICS OF GLYPHOSATE RESISTANCE MANAGEMENT IN CORN AND SOYBEAN PRODUCTION 1, 11 (2015) (noting effectiveness of weed control practices on one farm can depend on activities on nearby farms and the need for coordinated action by all neighboring farms).

33. *See* Robert K. Vischer, *Subsidiarity as a Principle of Governance: Beyond Devolution*, 35 IND. L. REV. 103 (2001) (discussing limits of subsidiarity to address problems).

soil, climate, natural predators, and other factors could be an ideal candidate for primary action at the state or local level.[34] For example, the United States has almost 600 different ecological systems that do not respect geo-political boundaries.[35] Attempting to regulate at the federal level could unnecessarily restrict access to plants in some regions in which there would be a low incidence of negative impacts. But when subsidiarity fails as state and local governments cannot or will not act—as discussed above with respect to regulation of just over 19% of harmful plant species—the federal government may provide necessary backstopping provisions. Unfortunately, federal programs designed to regulate noxious weeds also fall short based on their reactive, incremental, and piecemeal approaches.[36] A brief historical summary of federal programs follows.

In 1912, Congress enacted the Plant Quarantine Act (PQA) as an initial attempt to control the importation of nursery stock and control agricultural pests.[37] The PQA, however, exempted many potentially harmful vectors for invasive plants, including seeds, bulbs, roots, and bedding plants.[38] The 1957 Federal Plant Pest Act (FPPA) expanded federal authority to include all potential plant pests—not just pests to nursery stock—but still did not include actual plants that might cause damage on their own through invasion.[39] In 1974, Congress created a new regulatory program designed specifically to counter the negative ecological impacts of plants. The Federal Noxious Weed Act (FNWA) granted the USDA the authority to develop a federal Noxious Weed List to prevent the introduction or spread of harmful plants across the United States. The Plant Protection Act of 2000 (PPA) consolidated the PQA, FPPA, and FNWA into a single statute and retained the noxious weed list provisions.[40]

Like its state-level counterparts, the federal PPA does not provide authority to order removal of weeds on private lands, although there may be funding available to assist state or local governments' efforts to engage in weed control measures.[41] This funding, however, has been sparse and relatively ineffective.[42] Moreover, the USDA tends to include only well-established plants on its noxious weed list that have documented negative

34. McCubbins et al., *supra* note 20, at 41–42.

35. *Id*. at 41.

36. *Id.* at 43.

37. Plant Quarantine Act, ch. 308, 37 Stat. 315 (1912); *repealed by* Plant Protection Act, ch. 104, § 7758, 114 Stat. 438 (2000).

38. McCubbins et al., *supra* note 20, at 43.

39. Federal Plant Pest Act of 1957, Pub. L. No. 85-36, 71 Stat. 31 (1957); *repealed by* Plant Protection Act, ch. 104, § 7758, 114 Stat. 438 (2000).

40. Plant Protection Act § 438 (codified at 7 U.S.C. § 7701–7772 (2000)) (There are 87 terrestrial plant species contained on the federal list); 7 C.F.R. § 360.200(c) (2012).

41. Noxious Weed Control and Eradication Act of 2004, 7 U.S.C. § 7782 (2012).

42. McCubbins et al., *supra* note 20, at 44.

impacts, thus foregoing any preventative or precautionary benefits to national control.[43]

The result is a multi-layer regulatory program at state and federal levels that unfortunately lacks comprehensive coverage, reacts only to established noxious weeds rather than assuming a protective role, and at times does not make full use of scientific input as to the placement of species on the list.[44] Despite these limitations, there is a relatively high degree of weed control in the agricultural community due to the economic pressure weeds place on farming operations.[45] In recent years, adoption of genetically engineered herbicide-resistant crops has replaced integrated crop rotations, non-herbicide weed control, and cultural factors.[46] These weed control activities, often provided by contract-based custom applicators, tend to be individualized actions taken at the farm scale with little regard to broader impacts on the community or coordinated efforts,[47]despite general consensus among the weed science experts on best strategies to avoid resistance and manage weed infestations.[48]

C. Economic Incentives

Economic considerations drove the adoption of glyphosate-resistant crops.[49] Short-term economic decisions further drove the over-reliance on glyphosate as the primary weed control method and the subsequent development of glyphosate-resistant weeds.[50] Economics can also play a role in resolving the problem of herbicide-resistant weeds. Specifically, Livingston et al (2017) developed a model that combined a biological model for weed

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43. David M. Lodge et al., *Biological Invasions: Recommendations for U.S. Policy and Management*, 16 ECOLOGICAL APPLICATIONS 2035, 2039–42 (2006).

44. McCubbins et al., *supra* note 20, at 50–51.

45. David C. Bridges, *Impact of Weeds on Human Endeavors*, 8 WEED TECH. 392, 394 (1994).

46. A. Bryan Endres & Lisa R. Schlessinger, *Legal Solutions to Wicked Problems in Agriculture: Public-Private Cooperative Weed Management Structures as a Sustainable Approach to Herbicide Resistance*, 3 TEX. A&M L. REV. 827, 836 (citing David Ervin & Ray Jussaume, *Integrating Social Science into Managing Herbicide-Resistant Weeds and Associated Environmental Impacts*, 62 WEED SCI. 403, 406–07 (2014)).

47. *See generally* W.B. Ennis et al., *Impact of Chemical Weed Control on Farm Management Practices*, 15 ADVANCES IN AGRONOMY 161 (1963) (describing increased use of herbicides); Bryan G. Young, *Changes in Herbicide Use Patterns and Production Practices Resulting from Glyphosate-Resistant Crops*, 20 WEED TECH. 301 (2006) (describing replacement of sound weed and herbicide management practices with exclusive use of glyphosate for weed control).

48. *See* Norsworthy et al., *supra* note 3; *see also* LIVINGSTON ET AL., *supra* note 32, at 11.

49. Endres & Schlessinger, *supra* note 46, at 836.

50. *Id*. at 836–37.

growth, biological resistance to glyphosate, and the economics of weed management to explore farm-level options to actively manage resistance (long-term approach) versus ignoring resistance (short-term perspective).[51] The study found that managing resistance may reduce returns in year one, but increases returns in year two and all subsequent years.[52] Accordingly, a rational actor following the bio-economic model would actively manage resistance in order to increase returns beyond year one.

Yet most farmers do not actively manage resistance.[53] Barriers to a more active resistance management approach stem from economic and social considerations, such as the desire to deal with problems as they occur, expected future availability for a new herbicide with increased modes of action, focus on short-term profitability, lack of effective alternatives, and the need for increased management intensity relative to current practices using glyphosate or other broad-spectrum herbicides.[54] Accordingly, a practical solution to herbicide resistance must move beyond a rational actor economic model and address the human dimensions, including the social and cultural aspects of farming.[55] Land ownership patterns, access (e.g., farm tenancy for short versus long-term occupancy), and cultural barriers to collective actions can present significant obstacles to efficient herbicide-resistant management across landscapes. Landscape-level problems, such as herbicide resistance, require broad-based solutions with multiple actors. Efforts to adopt community-based weed management strategies, a promising approach to effective control, are in their infancy[56] and could benefit from more robust modeling and economic-based justifications to overcome existing social and cultural obstacles. To this end, an integrated, data-driven simulation model that predicts the spread of herbicide-resistant traits, while accounting for existing social and legal aggregations, can improve the capacity to slow the growth and prevalence of herbicide resistance in the agri-

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51. LIVINGSTON ET AL., *supra* note 32, at 11–12.

52. *Id*. at 13.

53. David J. Pannell et al., *Herbicide Resistance: Economic and Environmental Challenges*, 19 AGBIOFORUM 136, 145–46 (2016), http://www.agbioforum.org/v19n2/v19n2a05-frisvold.htm.

54. *See* Beckie & Hall, *supra* note 14, at 3; *see generally* T. C. Mueller et al., *Proactive Versus Reactive Management of Glyphosate-Resistant or-Tolerant Weeds 1*, 19 WEED TECH. 924 (2005); Edwards et al., *Benchmark Study on Glyphosate-Resistant Crop Systems in the United States. Economics of Herbicide Resistance Management Practices in a 5 Year Field-Scale Study*, 70 PEST MGMT. SCI. 1924, 1925 (2014).

55. Endres & Schlessinger, *supra* note 46, at 835; David E. Ervin & George B. Frisvold, *Community-Based Approaches to Herbicide-Resistant Weeds Management: Lessons from Science and Practice*, 64 WEED SCI. 609, 609 (2016).

56. *See generally* Ervin & Frisvold, *supra* note 55 (advocating for community-based approaches to weed management); Endres & Schlessinger, *supra* note 46 (same).

cultural context and facilitate adoption among the diverse stakeholders within the agricultural community.

IV. DATA AND MODELING NEW STRATEGIES FOR WEEDS AND HERBICIDE RESISTANCE

How to encourage diversified management among neighboring farmers remains a hurdle to large-scale management heterogeneity, and as such, the ability to evaluate weed-management efficacy and long-term resistance mitigation.[57] Both theory and empirical research demonstrate the potential for weed-management enhancement when area-wide application of appropriate integrated management technologies are deployed.[58] However, the scientific problem of weed gene movement and the consequences for agriculture cannot be separated from the social dilemma of implementation.[59] Many farmers do not own the actual land they farm,[60] leading to decisions based on short-term profits instead of long-term sustainability.[61] Existing models for combatting herbicide resistance do not incorporate or consider the effectiveness of strategies under conditions relevant to production farming, i.e., high incidences of shifting tenant occupancy on short-term leases with a patchwork of ownership patterns.[62]

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57. *See* A. Agrawal, *Sustainable Governance of Common-Pool Resources: Context, Methods, and Politics*, ANNOTATED REV. ANTHRO. 243–262 (2003); D. Ervin & R. Jussaume, *Integrating Social Science into Managing Herbicide-Resistant Weeds and Associated Environmental Impacts*, 62 WEED SCI. 403, 405 (2014); J.R. Lamicchane et al, *Integrated Weed Management Systems with Herbicide-Tolerant Crops in the European Union: Lessons Learnt from Home and Abroad*, CRITICAL REV IN BIOTECH 6 (2016).

58. Michael J Brewer & Peter B. Goodell, *Approaches and Incentives to Implement Integrated Pest Management that Addresses Regional and Environmental Issues* 57 ANNU. REV. ENTOMOL. 41, 42 (2012).

59. M. D. Owen et al, *Integrated Pest Management and Weed Management in the United States and Canada*, 71 PEST MGMT. SCI. 357, 358 (2014); Edwards et al., *Benchmark Study on Glyphosate-Resistant Crop Systems in the United States. Economics of Herbicide Resistance Management Practices in a 5 Year Field-Scale Study*, 70 PEST MGMT. SCI. 1924, 129 (2014).

60. Approximately 40% of agricultural land is leased nationwide with rates approaching 70% for some highly productive lands in Midwestern states. Edward Cox, *A Lease-Based Approach to Sustainable Farming, Part I: Farm Tenancy Trends and the Outlook for Sustainability on Rented Land*, 15 DRAKE J. AGRIC. L. 369, 372 (2010).

61. *Id*. at 384; *see also* Elise C. Scott & A. Bryan Endres, *Demanding Supply: Re-Envisioning the Landlord-Tenant Relationship for Optimized Perennial Energy Crop Production*, 25 DUKE ENVTL. LAW & POLICY FORUM 101, 121–22 (2014) (describing a new approach to long-term farm leases and moving away from generic good husbandry clauses in favor of more specific conservation practices and monitoring requirements).

62. J.A. Evans et al., *Managing the Evolution of Herbicide Resistance,* 72 PEST MGMT. SCI. 74, 74 (2016).

Data-driven models for evaluating strategies to slow the spread and increase mitigation of resistance must account for how management can be implemented within social frameworks. Specifically, farmers need sufficient practical examples and information to change management behaviors.[63] Incorporating real-world landscape data (ownership, tenancy duration, topography) and farm economics into spatial models of weed population dynamics and herbicide-resistance evolution could translate the abstract problem of herbicide resistance into terms that would aid local farmers in making actual management decisions.[64] Models, moreover, should structure potential management scenarios to provide options and comparisons that will allow communities to address issues of herbicide resistance collectively. Partnerships among local, spatially-aggregated stakeholders may provide the spatial continuity to combat regional common-pool-resources problems such as herbicide susceptibility.

Weed-control policymakers should incorporate public policy and legal management frameworks that have been successful in mitigating other common-pool-resource problems, like drainage and gas pooling and unitization.[65] Modeling efforts could inform development of legal frameworks for spatially coordinated and cooperative weed management that incentivize efficacious and economically attractive practices to mitigate herbicide-resistance spread over contiguous land areas.[66] But theoretical legal solutions, whether through regulation or private law,[67] face many of the same problems of implementation as the bio-economic models described above. Research has demonstrated that involving stakeholders in the decision-making process, such as via focus groups or semi-structured interviews can provide legitimacy to recommended management policies.[68] Incorporating focus group data on the human dimensions of the herbicide-resistance problem into existing bio-economic plus legal simulation models would more accurately inform the spatial spread in a way that science alone could not achieve.

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63. Lamichhane et al, *supra* note 57, at 3.

64. Lucia González Díaz et al., *Spatially Explicit Bioeconomic Model for Weed Management in Cereals: Validation and Evaluation of Management Strategies*, 52 J. OF APPLIED ECOLOGY 240, 241 (2015).

65. Endres & Schlessinger, *supra* note 46, at 845–49.

66. R. F. Durant & J.S. Legge Jr., *"Wicked Problems," Public Policy, and Administrative Theory: Lessons from the GM Food Regulatory Arena*, 38 ADMIN. AND SOC'Y 309 (2006)

67. *See, e.g.*, McCubbins et al, *supra* note 20 (recommending enhanced noxious weed regulations at the state level as well as a liability regime); Endres & Schlessinger, *supra* note 46 (recommending development of community based weed management agreements modeled on existing agricultural drainage district authorities).

68. Durant & Legge, *supra* note 66, at 3.

V. CONCLUDING THOUGHTS

Big data can enhance knowledge and understanding when considered in the appropriate context.[69] Enhanced and more powerful models that predict weed invasions or herbicide resistance are increasingly important tools to quantify the implications of a range of agroecological issues. Evaluating how resistance traits spread and "behave" in landscapes with realistic, complex spatial structures alone requires a diversity of data types and extensive computing resources. However, management strategies must be considered in the socio-cultural context of farming to adequately address potential solutions and their consequences. This is not an impossible task, although it requires nuanced understanding of multiple intersecting social relationships among stakeholders, such as between landlord and tenant, operators, and for-hire pesticide applicators, as well as with the chemical companies bundling products in a one-size-fits-all package for the farmer.

Changing agricultural practices and emerging weed problems, such as herbicide resistance, that require large scale implementation and evaluation demand increasingly sophisticated, multidisciplinary tools to provide decision support and recommendations. Landscape models of weed dynamics can help identify relevant spatial scales for effective management, but implementation will be inhibited by social and legal limitations to deploying management at large scales. An important area of focus for future legal research will be how to incorporate such considerations into functional frameworks to encourage small-scale modifications and partnerships necessary for large-scale cooperative management efforts. Models that combine ecological, economic, and legal data to examine management outcomes from cooperative aggregations will help inform weed management at large spatial scales and provide valuable incentives for individuals to invest in long-term cooperative decision-making.

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69. *See* Danah Boyd & Kate Crawford, *Critical Questions for Big Data Provocations for a Cultural, Technological, and Scholarly Phenomenon*, 15 INFO., COMMC'N & SOC'Y 662, 665–66, 670–71 (2012).