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Agrivoltaics with row crops as a pathway to solar farming on cropland



Madhu Khanna^{1,2}✉, Paul Mwebaze¹, Fahd Majeed¹, James McCall³, Mengqi Jia¹, Xuzhi Du⁴, Jordan Macknick³, DoKyoung Lee⁵, Bin Peng⁵, Nenad Miljkovic⁴, Evan H. DeLucia⁶, Carl Bernacchi⁵, Kaiyu Guan⁷, Bruce Branham⁵, Alan K. Knapp⁸, Greg A. Barron-Gafford⁹, Ruiqing Miao¹⁰, Andrea K. Gerlak⁹, Bijesh Mishra¹¹ & Nuria Gomez-Casanovas^{12,13}

Utility-scale solar expansion on Midwestern cropland in the US is intensifying food–energy land-use conflicts. Agrivoltaics, which co-locates solar panels with food/feed (row) crops, could ease community opposition by maintaining agricultural production while generating electricity. However, row-crop agrivoltaics remains difficult to scale because of yield tradeoffs, higher solar costs, and institutional barriers. Wider adoption will require new business models and community-centered land-use practices.

Solar energy production has seen rapid growth in the US in recent years and has accounted for the largest share of all new electricity-generating capacity additions since 2019^{1,2}. Utility-scale photovoltaic solar systems are the dominant form of solar development in the US, accounting for approximately 72% of cumulative solar capacity in 2025³. Utility scale solar energy is land-intensive and cropland is well-suited for it because it provides large, continuous tracts of relatively low cost, flat, well-drained land, with unobstructed solar radiation, in the proximity of grid infrastructure⁴. This lowers the capital costs of site preparation and enables economies of scale by combining multiple, nearby parcels into larger projects. In 2020, over 93% of utility-scale solar capacity was in rural areas with 66% of solar farms in the Midwest installed on land that was previously cropland⁵.

Cropland in the Midwest is intensively cultivated with row crops, corn, soybeans and wheat. The twelve states that constitute the Midwestern US (Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin) have 61.1 million acres in corn, 70.7 million acres in soybeans and 19 million acres in wheat⁶. These states contribute 87%, 86% and 55% of the total production of these crops in the US, respectively. Together these three crops occupy 80% of total cropland in these states. Thus, the cultural and place-based identity of farmers in these states is closely tied to the production of these row crops. The aggregate amount of US cropland being used for solar energy is relatively small, about

0.025% of farmland acres in 2021⁵; Cooper and Breneman⁷ estimate that a similarly low share of land under corn, soybeans and wheat was converted to solar farming by 2021. The upper bound on the area requirements of forecasted solar development is estimated to range from 1.1% to 2.4% of the area of croplands in 2050, even if we assume all new solar power capacity is installed on cropland⁸.

Although the aggregate amount of land under solar farming is expected to remain small^{9,10}, the share of cropland converted to solar farming can be large in some counties where farmland is located close to the transmission grid. As a result, there is growing opposition to the conversion of cropland to utility scale solar energy development resulting in bans in many counties in the US; more recent evidence indicates that local zoning and land use restrictions on utility scale solar developments have continued to expand in the US. To impede the buildout of solar power, at least 22 counties in nine states have set limits on the number of agricultural acres that can be used for solar power¹¹. This opposition is leading to delays and cancellations of solar projects and challenges for solar developers to access the lowest cost land for energy development.

Land lease rates offered by solar energy developers are often several-fold higher and more certain than the returns from crop production. This has led many landowners to benefit from leasing their land for solar development¹². A large share of these landowners in the Midwest do not

¹Institute for Sustainability, Energy, and Environment, University of Illinois Urbana-Champaign, Urbana, IL, USA. ²Department of Agricultural and Consumer Economics, University of Illinois Urbana-Champaign, Champaign, IL, USA. ³National Laboratory of the Rockies, Golden, CO, USA. ⁴Mechanical Science and Engineering, University of Illinois Urbana-Champaign, Urbana, IL, USA. ⁵Department of Crop Sciences, College of Agricultural, Consumer, and Environmental Sciences, University of Illinois Urbana-Champaign, Urbana, IL, USA. ⁶Department of Plant Biology, University of Illinois Urbana-Champaign, Urbana, IL, USA. ⁷Department of Natural Resources and Environmental Sciences, College of Agricultural, Consumer and Environmental Sciences, University of Illinois Urbana-Champaign, Urbana, IL, USA. ⁸Department of Biology and Graduate Degree Program in Ecology, Colorado State University, Fort Collins, CO, USA. ⁹School of Geography, Development & Environment, University of Arizona, Tucson, AZ, USA. ¹⁰Department of Agricultural Economics and Rural Sociology, Auburn University, Auburn, AL, USA. ¹¹School of Public Policy, Georgia Institute of Technology, Atlanta, GA, USA. ¹²Texas A&M AgriLife Research Center at Vernon, Vernon, TX, USA. ¹³Rangeland, Wildlife & Fisheries Management Department, Texas A&M, College Station, TX, USA. ✉e-mail: khanna1@illinois.edu

operate their land or live in rural communities; thus, some utility-scale projects can displace tenant farmers and transfer the income from the land from one region to another, with limited benefits to the local community in which it is occurring¹³. This can lead to uneven distribution of benefits and burdens within and across different population groups in rural and urban areas; concentrating benefits among distant landowners and solar energy developers located in urban areas while local communities face reduced access to land and higher land prices. Moreover, the loss of cropland to solar farming in small rural communities can make existing agribusinesses and supply chains unviable and create stranded infrastructure¹⁴. Stakeholder interviews also indicate opposition to solar farming because it poses a threat to aesthetics, identity, heritage, and place-based attachment for the community associated with farming^{10,13,15–16}. Conversion of agricultural lands to solar energy generation also raises concerns about how to best maintain other ecosystem services such as soil health and fertility¹⁷.

Agrivoltaics is an emerging solution that enables agricultural operations interspersed with panels or underneath raised panels on the same land. Agrivoltaics has the potential to provide numerous benefits, including reducing soil moisture loss and the need for irrigation in arid and semi-arid conditions, protection for crops from extreme temperatures and precipitation and higher yields of shade-tolerant crops, compared to growing these crops in full sun^{18–22}. Agrivoltaics has also been found to increase solar panel yield due to cooling by the vegetation surrounding it^{18,23}. A recent analysis shows the benefits of co-locating solar panels with perennial vegetation on corn acres in the Midwest for reducing nutrient run-off and providing local wildlife habitat²⁴. Current challenges to agrivoltaics include potential increased costs, reductions in energy generation, compatibility with existing farm operations and equipment, financing and insurance uncertainties, and the lack of market maturity.

Agrivoltaic sites emerging in the Midwest have largely integrated pollinator-friendly habitat or sheep grazing with solar panels; these are feasible without making modifications to a conventional solar farm. Experience with growing row crops interspersed with solar panels is limited to experimental sites²⁵ and yet to occur on large scale commercial operations²⁶. For agrivoltaics to be adopted at scale and address the perceived conflict between food/feed and energy production on cropland in the US Midwest, it will need to integrate row crop production with solar panels. A salient issue then is whether row crop agrivoltaics will appeal to solar developers, farmers and local communities. We provide a perspective on this with a focus on the Midwestern US, with millions of acres of land in industrial scale corn, soybean, and wheat production for livestock feed surrounded by well-developed infrastructure and supply chains to store, process, and deliver it. We rely on emerging scientific evidence, including from a multi-institutional, interdisciplinary research project funded by the US Department of Agriculture investigating the outcomes of co-location of agriculture and photovoltaic electricity systems.

Agrivoltaics with row crops in the US Midwest

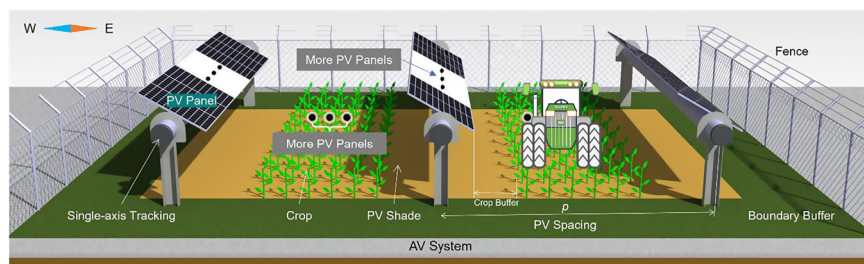
Growing row crops between or underneath solar panels at current scales of production in the US Midwest would require modifying panel height and spacing to reduce crop shading and accommodate conventional farming equipment²⁷, while still achieving sufficient solar energy production levels. (Fig. 1).

Row crops range in height from 1 meter (soybeans and wheat) to about 3 m (conventional corn)²⁸; thus, growing even relatively shorter crops can require raising solar panel height above the typical panel height (approximately 0.5 m at the lowest edge) in a conventional fixed-tilt solar farm. Agrivoltaic solutions involve making choices about the configurations of solar panels and crops, design and density of panels, type of panels used, and height and spacing between panels. Panels can be vertical, fixed tilt or sun tracking (with single or double axis) and be either monofacial or bifacial. These configurations affect how solar irradiance is distributed between panels and crops and determine the size of equipment that operate between panels²⁹. Additionally, row crop agrivoltaics can require increasing the spacing between panel rows to accommodate large agricultural equipment and allow for light to reach crops. In a typical single-axis tracking solar farm in the Midwest the distance between panels is 5.5 m; this is too narrow to operate conventional farm equipment needed for tilling, planting, and harvesting row crops. The operation of this equipment will require wider spacing between panel rows which is two to three times larger than that in a conventional solar farm. Additionally, production of crops next to panels also requires leaving some land unused as buffer areas around and under panels and at the ends of rows to enable farm equipment to turn and operate between panel rows²³.

Effect of agrivoltaics on row crop yields and energy generation

The implications of growing shade intolerant row crops, such as corn and soybeans, in the Midwest next to or underneath solar panels is limited to a few experimental sites^{25,30} and to simulation models that extrapolate findings to a regional scale^{31,32}. This research shows that the impact on crop yields varies across crops, climatic conditions and configuration of the agrivoltaics infrastructure. Kim et al.²⁵ found that while the impact of agrivoltaics farming on sorghum yield was insignificant, soybean yield declined by 75% relative to conventional full sun farming conditions. Similarly, the yield of corn grown underneath tall solar panels was found to decline substantially, with the negative impact increasing as the density of panels increased³⁰. Extrapolating these impacts of Agrivoltaics to agricultural lands that are primarily rainfed (not irrigated) using the Community Land Model version 5, Jia et al.^{31,32} show that agrivoltaics generate strongly divergent yield responses along east–west climate gradients. In the more humid eastern Midwest, panel shading reduces photosynthetically active radiation, causing substantial yield losses for corn (20–25%) and soybean (10–16%), whereas in more arid western regions, shading alleviates heat and water stress, leading to moderate losses in corn yield (10–12%) but gains in soybean yield (5–7%), under a scenario with a 33% solar panel ground coverage ratio defined as the proportion of land area covered by solar panels relative to the total site area^{20,33}. These process-based simulations further indicate that agrivoltaics enhance soil moisture and carbon assimilation in water-limited environments but reduce productivity in wetter regions due to light limitation. While panel-induced shading in an agrivoltaic setting will reduce crop yield compared to full-sun conditions, the shade can reduce interannual variation in yields caused by drought and, thus, increase resilience of agricultural production²². Thus, agrivoltaics has the potential to attenuate the effects of a changing climate in drought prone regions.

Fig. 1 | Schematic of an exemplary AV system design. 3D view of a proposed AV farm, showing the single-axis tracking PV panels installed at a set height to accommodate crop growth beneath. Crop growth is subjected to a dynamic shade environment due to east–west tracking of the PV panels, with potential for LED integration on panels to alter growth and physiology of crops. Crop buffer refers to the space between panels and crops. Source: Authors' original illustration.



The height, density, and configuration of the solar panel array in an agrivoltaics setting have implications for the choice of crops that can be grown and the crop rotations that can be practiced. Producing tall crops, such as corn, in an agrivoltaic setting requires installing substantially taller solar panels than with shorter crops like soybeans and wheat, since corn is about three times taller than soybeans and wheat. Shorter panels limit the ability to practice continuous corn or corn-soybean rotations that are typical in the Midwest and will restrict rotations to continuous-soybean or soybean-wheat. These rotations have been disfavored in the Midwest because they are less profitable³⁴.

While agrivoltaics may reduce crop yields per unit land it does enable energy generation on the share of land with solar panels. Under some conditions energy output per panel may increase due to vegetation-induced cooling²⁹. Evidence of the vegetation-induced solar panel cooling effect is mixed with some studies finding an increase in solar energy yield per panel under dryland conditions¹⁸ and others finding no effect in humid temperate conditions³⁵.

The concept of land equivalent ratio (LER) is an ecological metric that has been utilized to examine the efficiency of agrivoltaics compared to crops alone or solar energy alone. The LER is defined as the sum of the ratio of solar energy yield with agrivoltaics to solar alone and the ratio of crop yield with agrivoltaics to crops alone. It is a dimensionless metric that can be greater, equal to, or less than one. An LER value above 1 indicates a land use efficiency with agrivoltaics that is higher than with either crop production alone or solar energy production alone on that land. Agrivoltaics systems with specialty or forage crops in arid or semi-arid environments have often demonstrated LER values well above 1, sometimes exceeding 1.5^{18,20}. Even in the case of row crops in rainfed conditions, Kim et al.²⁵ and Jia et al.³² find that integrating row crops, such as soybeans and sorghum, with solar electricity generation achieves an LER above 1, despite shade-induced crop yield reductions. This indicates that the combined productivity (solar energy and crop output) of land is higher with the co-location of solar energy generation and crop production relative to crop only or solar energy production only on that land.

Effectiveness of agrivoltaics as a land saving approach to food and energy production

Although row-crop agrivoltaics has the potential for achieving an LER greater than 1, this does not imply that it will reduce the total amount of land needed to produce the same amount of crop output and energy yield. Conversion of land from conventional farming to agrivoltaics reduces the amount of land in a field under crop production (due to the installation of panels and buffer areas around panels) and reduces crop yield per unit land on the land planted with row crops between panels, due to shading by the panels. As a result of this the amount of crop output from the land under crop production in an agrivoltaic system is likely to be lower compared to the case where that land was entirely under crop production. This will imply the need for bringing more land into crop production elsewhere (or expansion of land along the extensive margin) if the goal is to meet the same levels of aggregate production of those crops. The extent to which this is the case will differ across locations, crops and climatic conditions. In arid regions, panel induced shade may have a less negative or even a positive impact on yield per unit land of certain crops^{22,32,33}. This increase in yield may partially offset the loss of land to panels and buffer areas and the extent to which cropland expansion will be needed to maintain total crop production.

Similarly, solar energy generation per unit land may decline due to lower density of panels in an agrivoltaics setting compared to a conventional solar farm, despite a potential increase in energy generation per panel. This will reduce total solar electricity generation or require more land for the same level of electricity production, which could exacerbate land use conflicts in communities.

Compared to the use of land for either crop production only or solar energy production only, which concentrates intensive row crop production in the most productive land areas and places solar energy installations in the

lowest energy production cost areas, agrivoltaics could lead to the need for more land area to meet the same aggregate amount of solar energy and crop production. Khanna et al.²³ find that agrivoltaics deployment with soybean production could require approximately 20% more land to achieve the same soybean output as a conventional crop-only field in the U.S. Midwest. An agrivoltaics system would lead to less-intensive crop and less-intensive solar energy production and spread it out over a larger land area; thereby increasing the extensive margin of crop and solar energy production, although maintaining agricultural land in production, unlike conventional utility-scale solar generation. This can raise concerns about converting non-cropland to crop and energy production and be counter-productive to conservation goals.

An alternative approach to mitigating land use conflicts due to the conversion of cropland to solar farming is to use low quality marginal land for solar energy generation and keep productive cropland in crop production. Using low quality marginal land for solar energy generation offers a high value use for that land. However, the availability of economically marginal land, that does not yield an economic return under crop production, is relatively limited in the Midwestern US³⁶. The availability of marginal land is expected to increase in the future in some regions of the US, with a changing climate³⁷ and this could increase incentives to diversify to other uses.

However, the potential for using marginal land for solar energy development depends on its suitability for solar energy production and its location in areas where grid interconnection is feasible. High costs of expanding the transmission network and high rate of loss of energy with the transmission of solar energy over long distances are leading to concentration of utility scale solar energy installations in locations in the proximity to the transmission grid and to consumers. Low quality land, with high yield variability and low profitability is present at sub-field levels; 16–38% of land in ten Midwestern states was characterized as having unstable corn and soybean yields³⁸ and 27% of cropland, at a sub-field level, was found to be unprofitable in Iowa in 2015³⁹. However, economies of scale, ease of operating conventional equipment and cost efficiency lead to a preference for operating large contiguous tracts of land for solar energy installations and crop production. Installing a patchwork of solar panels on low quality land at sub-field levels may impose high costs and inefficiency of production with existing equipment. This could change in the future with the adoption of smaller electric tractors and robots that can be operated in smaller sub-field areas effectively.

Economic incentives for row crop agrivoltaics for farmers and solar developers

The preference of solar developers and farmers for solar alone or crops alone, respectively, compared to agrivoltaics will depend not only on effects of productivity but also on profits for the solar developer and the farmer. A higher LER does not indicate higher profitability, and therefore, does not ensure that solar developers and farmers would be economically motivated to choose agrivoltaics instead of solar farming or crop farming alone, respectively. The key economic drivers of the choice to adopt agrivoltaic solutions for a solar developer include the effect on the upfront capital costs and the operating and maintenance costs which include managing vegetation on the solar farm. Raising the height of panels and burying the electricity cables underground to enable crop production significantly raises the initial installation costs of panels (30–40%) due to the need for taller steel posts, deeper foundations, more reinforced supports and greater labor time⁴⁰. These costs could potentially be offset in part by lower vegetation management costs and lower land lease costs.

Khanna et al.²³ show that agrivoltaics configurations are currently economically uncompetitive for utility scale solar developers, relative to conventional solar farming systems. Taller panels can potentially more than double total system costs and may raise the cost of solar electricity to be more than twice that from conventional solar energy generation alone, despite modest gains in energy output and savings in land or vegetation management⁴¹. Agrivoltaics could also reduce economies of scale that are

achieved by concentrating solar energy generation in its most suitable locations and lead to transmission losses by increasing the distance from the transmission grid. Moreover, agrivoltaics installations that span county lines and that require coordination of crop choices and management across multiple farm owners will raise the transaction costs for solar energy development. Solar developers are, therefore, not likely to find it profitable to make any alterations to the height and spacing of panels.

Solar developers could have greater interest in agrivoltaics in the presence of regulatory incentives that could be provided at various levels of governance, including, state and local levels and can include tax credits, favorable zoning laws, easier siting approvals and property tax abatement⁴², which could make projects more financially viable. Utility-based programs for agrivoltaic installations and market based mechanisms such as consumer willingness to pay a higher price for electricity generated from agrivoltaics installations can also influence a solar developer's decision to pursue agrivoltaics. Agrivoltaics may also increase ease of project development due to improved community acceptance. Survey evidence indicates a willingness to pay a higher price for electricity from agrivoltaics compared to solar farming alone because consumers perceived less negative impacts of agrivoltaics on landscape attractiveness as compared to solar panels alone⁴³. Solar developers indicate reducing community opposition and obtaining social license to operate as key motivators for agrivoltaics development, despite concerns about financial costs and associated risks (Mishra et al., manuscript under review)⁴⁴.

The economic motivations for farmers to adopt agrivoltaics instead of solar farming or crop farming will depend on the relative returns to land from these alternative uses and the modifications to agricultural operations required. For non-operating landowners seeking to earn the highest return on land, solar farming offers rental rates that are several-fold higher and more certain than the agricultural land rental price; thus, leasing land to solar generation alone is likely to be the preferred choice. Empirical evidence indicates that solar lease payments can range from approximately \$500 to over \$2000 per acre annually, compared to typical annual cropland rental rates of \$150–\$300 per acre, depending on location and land quality^{40,45,46}.

For owner-operators leasing land to a solar developer, agrivoltaics offers a mechanism to maintain access to farming and diversify income sources from the same land. Co-location can increase total land productivity and provide more stable income through a combination of crop output and energy-related income⁴². With high lease rates and returns for vegetation management, the overall returns to cropland for an owner-operator can be higher and less risky than from using land for crop production alone despite lower crop yields on the farmed portion of the land. However, the need to switch cropping systems or change crop rotations and acquire new farming equipment can raise the operational cost of crop production. Farming between short panels and narrow rows may appeal to some small and beginning farmers or tenant farmers, who may otherwise not have access to agricultural land, and who are willing to modify crops planted and equipment used. Moore et al.¹² note that commercial farmers identifying themselves as corn and soybean farmers do not view producing other crops for forage or other specialty markets as farming and are skeptical about the feasibility of agrivoltaics.

Agrivoltaics as an enabler for solar farming on cropland

Looking beyond solar developers and farmers, a key question is whether row crop agrivoltaics can improve community acceptance of solar farming on cropland. By enabling agricultural production and preventing large tracts of land under solar farming only, agrivoltaics allows for preservation of the social fabric and place-based attachment for a community experiencing utility-scale solar development. By permitting tenants to continue farming, agrivoltaics can reduce the adverse impacts of solar energy production on agricultural employment. With low density solar energy generation, agrivoltaics can spread out the economic benefits of solar farming over a larger land area and may be perceived as being more equitable than solar farming alone where benefits may be concentrated among a few landowners. Surveys

in the US indicate that over 80% of respondents would be more likely to support solar development in their community if it is integrated with agricultural production⁴⁷.

However, there is currently no standardized definition of agrivoltaics, in terms of solar panel configuration, panel density, panel height and ground coverage ratio. Utility scale solar developers have limited motivations for modifying spacing or height of panels and may view agrivoltaics as a nominal technology-fix to address land use conflicts and gain acceptance by the agricultural community rather than as an approach that addresses their underlying concerns with solar farming on cropland.

Additionally, under the existing approach to solar farming, energy generation and crop production represent distinct industries with solar developers lacking familiarity with crop farming and farmers lacking expertise with the solar industry. Developers finance the project and provide landowners with a fixed lease rate for the lifetime of the project. The returns to the land from solar energy generation may create some solar-related jobs locally but most fiscal resources leave the community. This would not fundamentally change even with agrivoltaics if landowners are simply leasing land to the developer and have limited opportunities for co-optimizing food and energy production on the same land. There is currently a lack of alternative models for corporatization of an agrivoltaics installation by a community of farmers. As a result, current concerns with solar farming being imposed on farmers (rather than co-developed) and leading to a transfer of wealth from the land and the local community to urban areas will persist with agrivoltaics as well. New agrivoltaics business models that promote smaller-scale, farmer- or community-centric installations in which the farmer owns or co-owns solar energy development to generate solar energy for on-farm use and to supply the excess to the grid may provide more socially acceptable opportunities for co-producing row crops and solar energy.

Agrivoltaics is an emerging industry that is currently being offered as a solution to address opposition from the agricultural community by integrating agriculture with minimal modifications to solar energy generation. It is important to note that agrivoltaic approaches can be as diverse as agriculture itself, solar infrastructure integrated with specialty crops, pollinator plants, pastures and rangelands and even orchards and vineyards⁴⁸. In the case of row crop agriculture it is clear that agrivoltaics is currently sub-optimal from agronomic, economic, and electricity-generation perspectives and thus challenging to scale up. For row-crop agrivoltaics to enable a more comprehensive solution to the conflicting demands on land, significant changes in technology (that co-optimizes co-located crop and solar energy production) will be needed. This could be particularly advantageous in the future with a changing climate, increased variability in climate conditions, and increased availability of cropland at the margins that is less suitable for conventional crop production. In addition to technological advancements institutional and market support could lead to more widespread deployment of agrivoltaics. These institutional changes could include a shift from utility-centric models of solar energy generation and agrivoltaics ownership to farmer-owned and operating systems with more distributed models of energy production. The choice between single function land use vs multi-functional agrivoltaics hinges on the specific local context, shaped not only by economic factors but also by social, cultural, and community-driven influences. Transitioning land for solar energy development will necessitate collaboration with the agricultural community to establish mutually acceptable land-use practices that address social equity concerns and the potential disruptions caused by solar energy development to established ways of life in agricultural communities, rather than relying solely on transactional arrangements.

Data availability

No datasets were generated or analysed during the current study.

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Author contributions

M.K. conceptualized the manuscript and led the writing. P.M., F.M. and J.McC. contributed to the analysis and literature review. X.D. prepared Figure 1. M.J., J.McC., J.Ma., D.L., B.P., N.M., E.H.D., C.B., K.G., B.B., A.K.K., G.A.B.-G., R.M., A.K.G., B.M. and N.G.-C. contributed materials, interpretation, and manuscript review. All authors reviewed and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to Madhu Khanna.

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