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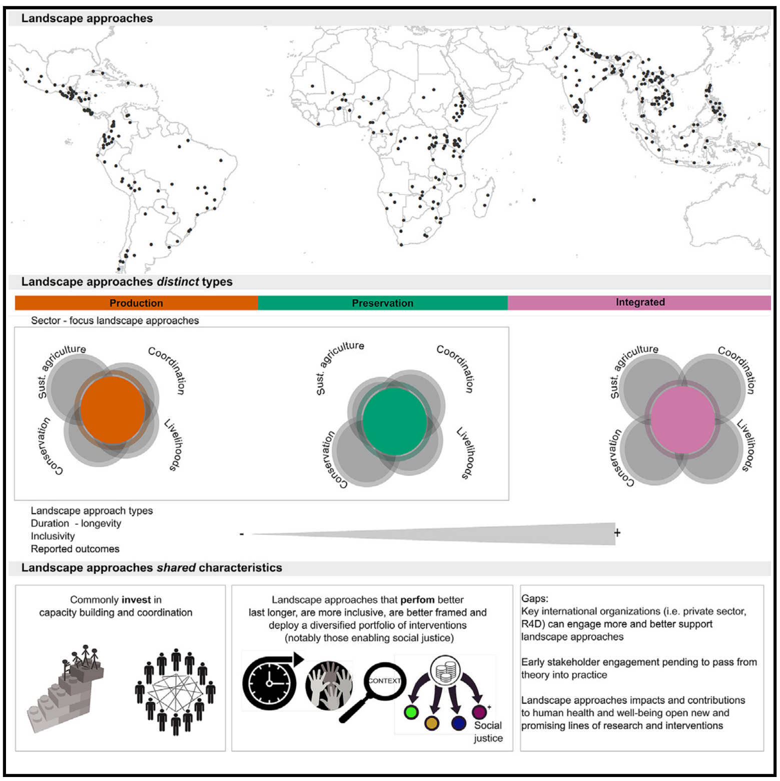
Reconciling conservation and development requires enhanced integration and broader aims: A cross-continental assessment of landscape approaches

Graphical abstract



Highlights

- We learn from 380 practitioners using landscape approaches in the subtropics and tropics
- Globally, three distinct forms of applying landscape approaches exist in practice
- Performance is driven by duration and investments across goals
- International stakeholders are key partners but often have misaligned aims

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In brief

Reconciling conservation and development is urgent, particularly in tropical and subtropical regions where forest-agricultural landscapes are under pressure. To this end, cross-sectoral and integrated approaches to managing agricultural landscapes are considered necessary, potentially able to balance divergent interests and enable coordinated action. In practice, they are diverse. We analyzed the features of landscape approaches across three continents and identify three types, assess their performance, and provide practical lessons to improve their design and implementation to benefit people and nature.

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Reconciling conservation and development requires enhanced integration and broader aims: A cross-continental assessment of landscape approaches

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SCIENCE FOR SOCIETY In subtropical and tropical regions, agricultural landscapes supply essential food, feed, and fiber, among various ecosystem services to both rural communities and growing cities worldwide. These landscapes are biodiversity hotspots and cultural centers but face pressures from climate change, commodity trade, poverty, and environmental degradation. Holistic efforts like landscape approaches (LAs) are increasingly used to balance trade-offs at the landscape level and address these interconnected challenges to achieve multiple goals, such as conservation, sustainable production, livelihoods, and governance. Our results from three continents highlight distinct ways to apply LAs, despite shared challenges hindering their performance. All LAs focus on capacity building and coordination, while long-term support, inclusion, and a diversified portfolio of interventions improve performance. Our findings offer actionable insights, notably for international organizations, to enhance support for LAs.

SUMMARY

Expectations for agricultural landscapes in subtropical and tropical regions are high, aiming for conservation and development amid climate change, unfair trade, poverty, and environmental degradation. Landscape approaches (LAs) are gaining momentum as means to reconcile expectations, although they face multiple challenges, including unclear distinctions among LAs and stakeholder involvement. We studied 380 LAs from three continents via questionnaires with landscape managers (2012–2015 and 2021) and identified three LA types through cluster analysis: an "integrated" type with longer-term, multisectoral goals involving various stakeholders early in the design and two shorter-term types focused on sectoral priorities of preservation or production. Better-performing LAs are associated with longevity, inclusivity, and diversified investments across goals, notably those enabling social justice. International stakeholder analysis shows broad support for LAs but identifies gaps between support and LAs' needs. The growing interest in LAs is promising. Yet, underpinning effective and lasting LAs that reconcile multiple expectations requires better support.

INTRODUCTION

Multifunctional landscapes are crucial to achieving development, conservation, land degradation, and climate change goals. However, efforts to achieve these goals individually through site-level and siloed interventions such as land sparing,[1] green revolution innovations,[2] or "fortress" conservation[3] often exacerbate environmental challenges and social injustices,

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particularly in tropical and subtropical regions.[4] Experts in development and conservation argue that landscape approaches hold promise to pursue multiple goals simultaneously, achieving effective and equitable multifunctionality.[5–9] Landscape approaches can help to bring together stakeholders from different sectors for collaborative and integrative planning to develop landscape-level interventions that enhance socio-ecological systems' long-term resilience and sustainability.[10–12] In practice, landscape approaches lack a standardized definition and spatial delimitation but typically subscribe to a set of widely accepted principles.[13,14] While these principles and aims are generally acknowledged, landscape approaches take multiple forms and go by various names that involve multiple concepts, such as ecosystem approach, jurisdictional approach, biosphere reserve, integrated watershed management, biological corridors, foodscapes, and foodsheds, among others.[12,15] Thus, the term "landscape approaches" (LAs) encompasses a diverse set of efforts to tackle complex challenges at the landscape level.

The evidence confirms the wide application of LAs, which cover different contexts and multiple continents.[12,13,16–20] However, in this suite of apparently diverse initiatives that identify as LAs, there may be discernible distinctions in their efforts on the ground. Regional evidence from Latin America and the Caribbean (LAC),[21] a global literature review,[7] and a group of case studies from the Satoyama Initiative[12] point to distinct types of LAs. Yet, whether those types exist or persist in other regions, such as Asia or Africa, is unclear. Similarly, it's unclear whether the distinct types of LAs face the same range of barriers to operationalization identified in the scientific literature (e.g., Vermunt et al.,[22] Pedroza-arceo and Weber,[23] and Meli et al.[22–24]) and, more importantly, whether the factors associated with LAs' performance are shared or vary across types. While substantial knowledge exists on various aspects of LAs as a general concept,[6,9,10,16–18,20,25,26] detailed analyses of types and their performance are available only for LAC.[21] Therefore, a cross-continental analysis of the comparable regional assessments from LAC,[16] Asia,[17] and Africa[18] is essential for understanding what LAs are, how they differ, and how performance is associated with contexts and types. More broadly, identifying LA-type-dependent enablers will be central to guiding, with evidence, the growing endorsement and support of LAs by international organizations, practitioners, funders, and private enterprises.[6–9,26]

Multiple intervention strategies that enable achieving sustainable development and conservation are put forward and implemented in LAs. For example, intervention strategies to improve agriculture sustainability cover a wide range of practices, including conventional and, more recently, agroecological practices, notably in (sub)tropical regions.[27–29] Similarly, intervention strategies may be used to nudge behavioral change through standards or certification, land use zoning, or coordination.[29] Also, intervention strategies can focus on enabling certain ideas of social justice through income generation, training, food security, or health.[30–32] In practice, evidence of how those intervention strategies or bundles of strategies are implemented across LAs and how these influence LAs' performance remains limited. Carmenta et al.[21] analyzed LAs in Latin America and proposed that three central intervention strategies (aiming to foster behavioral change, enable social justice, or improve agriculture sustainability) were operating within and across their typology of LAs, and training and coordination were the most common sets of interventions.[21] However, they found no consistent pattern between intervention strategies and performance across LA types.[21] This is an important knowledge gap, and empirical evidence of how intervention strategies used by LA practitioners are associated with performance is essential to better support LAs and understand their effectiveness.[6,14,26]

Interest in LAs is high, despite the substantial and sustained support these complex efforts need. Some LA proponents suggest three catalysts for achieving desired change in LAs: governance, markets, and finance.[9] The scientific literature has focused on the governance aspects of LAs,[22,33,34] with the other two catalysts of markets and finance receiving less attention. Markets and finance can greatly contribute to delivering multiple benefits at scale and innovating synergistic solutions to complex challenges.[3,9,19] Yet, the involvement of international stakeholders, including organizations directly linked to markets and finance opportunities, such as the private sector, remains contested. Some authors indicate a high involvement,[35] whereas others flag an absence or low and conflicting engagement.[36] The engagement of other international stakeholders indirectly supporting market and finance access in LAs by generating evidence and leveraging funds and capabilities, such as "research for development" (R4D) organizations (R4D), remains heavily understudied. Yet, certain R4D agencies, such as CGIAR, deliver public goods that influence the type and management of agricultural lands and impact the potential for multifunctionality in these areas. Increasingly, the CGIAR recognizes the landscape as a unit of intervention and analysis for systems transformation, particularly for achieving multiple interconnected human, ecological, and agricultural development goals.[37] Despite their interest, action and influence in this space, there has been little empirical work assessing how R4D advances the concept and implementation of LAs.

Here, we fill these multiple knowledge gaps by analyzing the full set of 357 LA projects, programs, or research initiatives, collected in 2012–2015 and deriving from three regional assessments (LAC, Asia, and Africa)[16–18] (hereafter referred to as the "cross-continental dataset"). We excluded the European LA assessment data due to differences in protocols precluding comparative analyses. Additionally, we supplemented the cross-continental dataset with additional data collected in 2021 from a set of 23 LAs with CGIAR researchers leading or engaging and covering the same three regions (hereafter referred to as the "extended dataset"). The extended dataset enabled a deeper evaluation of a key R4D consortium (CGIAR) contributing to sustainable development via LAs in the studied regions. We analyzed the LAs through a cluster analysis by using multiple-factor analysis (MFA) and the hierarchical clustering of principal components (HCPC). The cluster analysis enabled us to identify central distinctions and similarities between LAs' operationalization across continents. Additionally, we conducted a non-parametric analysis to identify variables associated with LAs' performance in the cross-continental dataset and each cluster of LAs. Last, we analyzed all listed partners and specifically analyzed international organizations or stakeholders engaged to assess those present or missing across LAs. Our findings suggest distinct ways to operationalize LAs, resulting in different performance levels. We also found common challenges shared across LA types, and our results support the notion that "how" these complex efforts are supported could be more relevant than the "what" is supported. Our research, grounded on LAs from three continents, contributes to advancing the theoretical knowledge of LAs and pinpointing key opportunities to improve their practical application. We provide actionable guidance for international organizations and stakeholders to more effectively support LAs in achieving multiple goals that benefit people, nature, and future generations.

RESULTS AND DISCUSSION

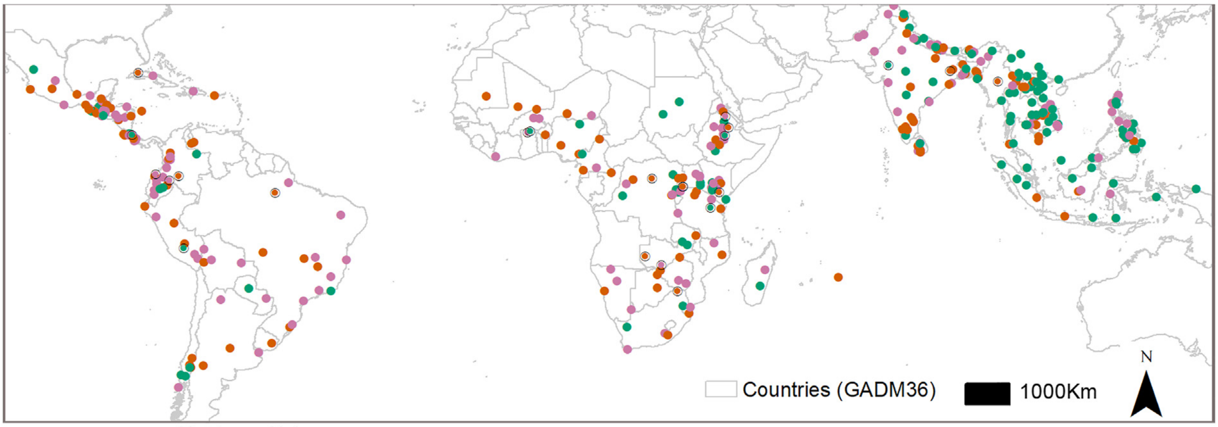
Distinct LA types implemented on the ground

It is important to first note that the data used in this analysis is based on questionnaire data reported by individuals leading or managing the LAs. This may introduce bias, as respondents could conceivably choose to submit information that they perceive would make a positive impression or, conversely, withhold information they consider to be negative. However, respondents were made aware that donors would not view the data and that the questionnaire was to learn from current strategies, including their difficulties and barriers, to advance research and practice, which we hope helped to reduce bias. Nonetheless, the potential for introduced bias exists and should, therefore, not be overlooked when interpreting the results (see Study limitations and caveats for more details).

The cluster analysis on the cross-continental dataset (357 LAs) confirms that central distinctions between LAs exist[7,12,21] (Figure 1). This finding remains consistent when assessing the extended dataset involving the CGIAR-associated LAs (Table S4). A wide range of categorical and quantitative variables, strongly and significantly associated with each cluster (or "type" of LA). These distinctions cover multiple features, including duration since inception (LA longevity), dominant land uses, management options employed, motivations driving LA inception, sectors and stakeholders engaged, and actions or investments led by LAs (Figures 2 and 3; Table S3). Validation of the clusters is strong, with <10% (8 of 100) being misclassified through a different test (Table 1; experimental procedures; Table S1).

We labeled the LA types evident within the clusters as "preservation," "production," and "integrated" and thereby highlight the salient differences. For example, the most common actions in production LA types relate to agriculture, while four of the seven actions in the conservation domain were pursued only rarely (<20% production LAs) (Figure 2; Tables S2 and S3). Preservation LA types focus on the conservation of water, soil, or forest resources. We selected the term "preservation" to avoid confusion with the conservation domain in the original questionnaire. In preservation LA types, actions such as "other community-based natural resource management activities" and "training or capacity building programs to support natural resource management" were dominant in these landscapes (>80% preservation LAs) (Figure 2; Tables S2 and S3). Meanwhile, integrated LA types invested in actions across domains (Figure 2; Tables S2 and S3). We found that production- and preservation-oriented LAs tend to list significantly narrower motivations, fewer stakeholders and sectors involved, and fewer and less diverse actions across domains (e.g., sustainable agriculture, conservation, coordination, and livelihoods), which aligns with previous LA-type assessments that also identified more sectoral-like LAs.[7,21] Therefore, even though landscape managers identified their initiatives as integrated LAs, in fact, they appear only marginally integrated and, instead, the preservation and production types tend to have a sectoral lens focusing on specific goals. In contrast, those clustering as integrated types did have broader aims, actions, and stakeholder engagement and can, therefore, be considered LAs reflecting more integrated efforts (Figure 2; Table S3).

Although commonly and collectively called "integrated LAs" in the scientific literature, only a third of LAs in our dataset appeared as integrated LAs (Figures 1 and 2). Compared with the production and preservation LA types, the integrated LAs focus on more diversified landscapes with a greater diversity of prevailing major land uses (Figure 2B). These integrated LAs last longer, involve more sectors (e.g., agriculture and natural resources; Table S3) and actively invest across domains (Figures 2A, 2E, and 2G). They also tend to engage with more stakeholders, such as local



Clusters of LAs

+23 LAs - CGIAR 2021	Cross-continental dataset 2012-2015	Latin America and the Caribbean - LAC	Africa	Asia	Total
	Production	41 (11%)	32 (9%)	40 (11%)	113 (32%)
	Preservation	13 (4%)	21 (6%)	84 (24%)	118 (33%)
	Integrated	50 (14%)	34 (10%)	42 (12%)	126 (35%)
	Total	104 (29%)	87 (24%)	166 (46%)	357 (100%)

Figure 1. Distribution and distinct types of LAs across three continents (extra 23 LAs identified in 2021 and cross-continental database identified in 2012–2015)
LAs are color coded based on the cluster or type.

government leaders or staff, local farmers' associations, local non-governmental organizations, local universities or research centers, and women's associations (Figure 2F and Figure 3). Stakeholders—notably local stakeholders—in the integrated LAs exhibit greater participation in early design stages (Figure 2). Integrated LAs also mobilize more intervention strategies commonly used in conservation and development (Figure 2H).

Therefore, the integrated LAs align most closely with seminal work describing good practices for LAs,[10,35] previous descriptions of integrated LAs from literature reviews,[7] and regional typologies of LAs.[21] Carmenta et al.[21] found two integrated types when conducting the LAC regional assessment: one more focused on "participation and legislation" and the other on "certification, institutions, and participation." Yet, when analyzing the cross-continental data, this differentiation disappears, resulting in only one cluster of integrated LAs. Overall, the characteristics of integrated LAs suggest that these efforts tend to incorporate inclusive landscape governance at the design stage and potentially incorporate local knowledge, social relations, stakeholder needs, and grounded aspirations. Encouragingly, although the integrated LAs in the cross-continental dataset only represent about one-third of all approaches, they are distributed evenly across the three continents (Figure 1).

Strong differences distinguish the sectoral production and preservation LAs. Production LAs were developed in response to more motivations across domains but aimed to resolve issues within shorter time frames and involving fewer sectors, stakeholders, and actions (Figures 2A, 2D–2H, and 3;; Table S3). Preservation LAs exhibit the most comprehensive management options emphasizing monitoring and evaluation, adaptive management, and baseline and geospatial assessments (Figure 2C; Table S3) but had narrower motivations for LA inception (Figure 2D). Yet, preservation LAs mobilized more actions across all domains and intervention strategies, except those related to agriculture (Figures 2G and 2H; Table S3).

Multiple factors, such as local conditions, priorities, and the overall landscape starting point, may determine the LA type applied.[7,12,19] For example, LAs in landscapes predominantly comprised of conserved and protected areas with high cultural values vs. predominantly degraded lands with fragile human-nature interdependence face different challenges and demand contrasting efforts to operationalize LAs.[13] However, the predominance of LA types with sectoral lenses raises the question of whether this dominance is due to the landscape's initial starting point or to a large proportion of LAs having their origins in more sectorial approaches. The latter may now be evolving and adapting toward integrated LAs or simply just adopting new nomenclature around their activities to maintain access to funding, given the rising interest and investment in the concept.

All landscape managers agreed with our LA inclusion criteria when completing the survey and believe their interventions to classify as an LA (experimental procedures). This potentially means that, within LAs with a sectoral focus, their efforts are potentially a step further toward integration than purely sectoral projects; however, we did not collect attribute data on the latter. It may also mean that there are divergent understandings of what constitutes an LA, which has been cited as a potential problem arising from the current lack of definition, or, in the worst case, that the term is being co-opted and applied to essentially sectoral approaches. However, all initiatives are likely attempting some form of integration owing to the finding that, on average, none of the LA types presented null or extremely low investments across domains or investment strategies, except for increased inputs (Figure 2). This evolution from sectoral to integrated approaches has been reported in the scientific literature from a small set of case studies.[19]

Figure 2. Characterization of LA types (clusters) based on continuous variables

Values are standardized for comparability and represent the standardized mean, standard errors, and variables strongly differentiating each cluster according to the MFA/HCPC analysis. Values diverging significantly from the mean according to the v test (p value $\leq$ 0.05) are indicated as – or + .

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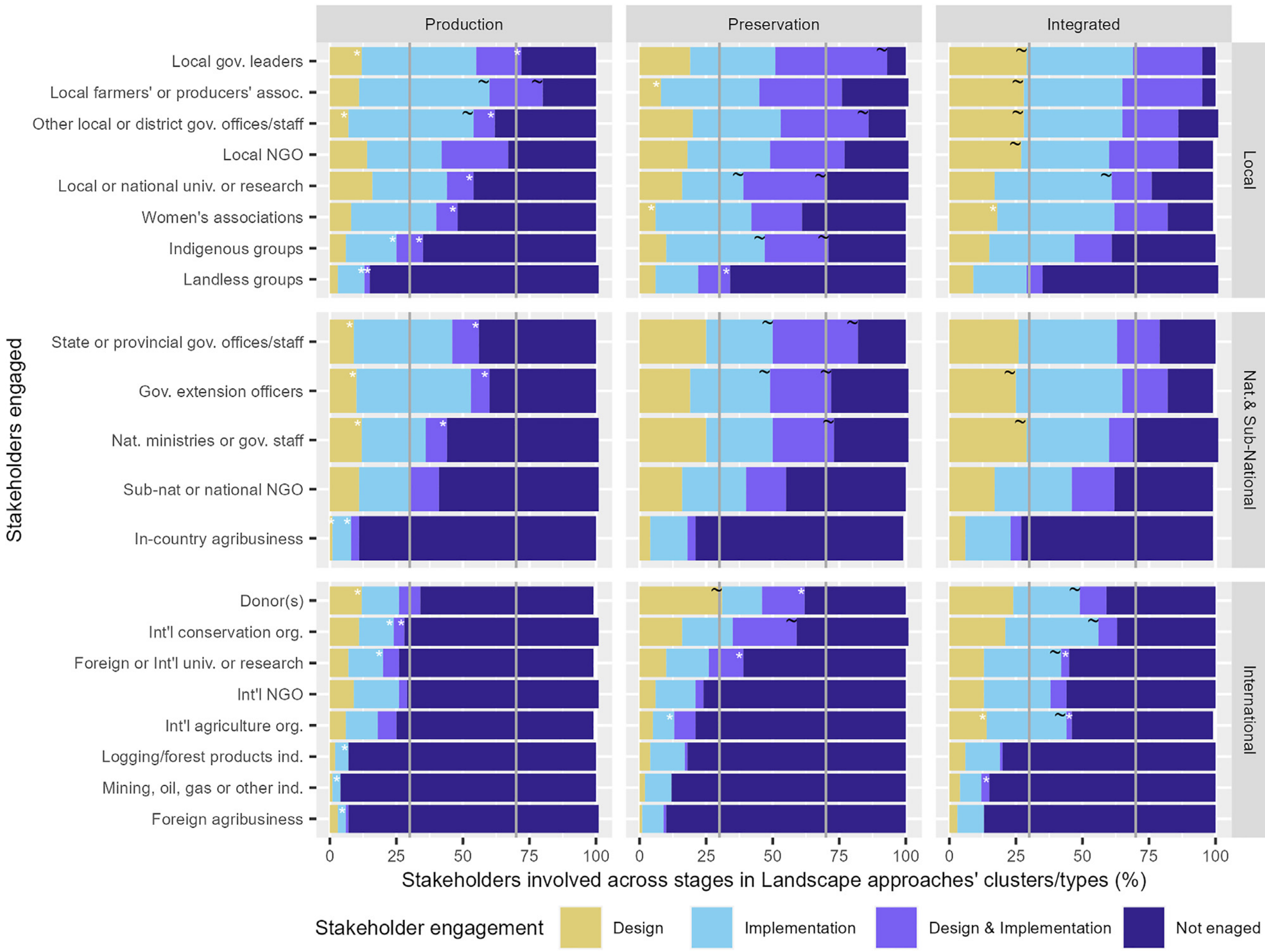

Figure 3. Proportion of stakeholders by level involved in each type and at different stages (design, implementation, and design and implementation)

* and ~ indicate variables strongly and significantly associated with each type or cluster of LAs according to the $\chi 2$ test (p value < 0.05), and variables can be either rare (<20% LAs in each type) or common (20–80% LAs in each type), respectively. See Tables S2 and S3 and the data[38] for more details. NGO, non-governmental organizations.

The specific case of R4D offers further learning related to sectoral LA types. The cross-continental dataset has 38 LAs with CGIAR engagement, of which 29 clustered in sectoral types (17 production LAs and 12 preservation LAs). Similarly, of the additional 23 LAs identified only through the CGIAR networks, 18 of them clustered in sectoral types (12 production and 6 preservation; Table S4C). Multiple reasons may explain the coherent dominance of sectoral LAs in R4D organizations: 76% LAs in 2012–2015 and 78% LAs in 2021. For example, efforts to move solely from work centered on technology adoption to conducting systems-oriented research in and for development are taking place but are relatively recent.[39] Besides, researchers have flagged some fundamental discrepancies between the support provided by international stakeholders and what LAs need, including discrepancies in timelines (e.g., short-term versus long-term support), investment priorities that encompass global versus local needs, top-down versus bottom-up governance, narrow versus holistic monitoring systems, and funding targeted to increase technology adoption versus strengthening social empowerment, among others.[39–43] Therefore, the inertia of technology-centered culture and projects, mixed with short-term funding and engagement, constrains LAs maturation (e.g., Douthwaite et al.[39]). Addressing and understanding these discrepancies is needed to support, rather than hinder, the locally driven long-term and process-oriented efforts central to integrated LAs.

(A–G) Questionnaire themes.
(H) Actions post classified into intervention strategies commonly used in conservation and development are presented but excluded from the MFA/HCPC analysis as well as total stakeholders involved. See Table S3 for the categorical variables strongly differentiating each type (cluster). Intervention strategies are as follows: AS aims to improve agriculture sustainability, BC aims to foster behavioral change; and SJ aims to contribute to social justice by fostering empowerment, autonomy, health, and equity.

Table 1. Top variables explaining total outcome variance in four performance analyses

	Performance analyses							
	Cross-continental dataset		Production LAs		Preservation LAs		Integrated LAs	
n	357		113		118		126	
Explained var (%)	37.38		8.59		24.4		12.2	
Variables (units)	Avg. rank	No. metrics	Avg. rank	No. metrics	Avg. rank	No. metrics	Avg. rank	No. metrics
Total intervention strategies used (%)	1	5	1	5	2	5	1	5
Longevity	3	5	5	4	1	5	3	5
Intervention strategies enabling social justice (SJ) (%)	3	5	3	5	4	5	5	5
Stakeholders involved during implementation (no.)	22	3	9	3	5	5	7	4
Total motivations (no.)	5	5	26	4	7	4	36	3
Intervention strategies enabling agriculture sustainability (AS) (%)	5	5	8	4	40	0*	2	5
AS: agro-ecological practices (%)	7	4	5	5	48	0*	4	5
SJ: tenure, equity, culture (%)	11	3	10	2*	9	4	35	3
Intervention strategies enabling behavioral change (BC) (%)	11	4	19	2*	7	5	29	0*

Variable values show the average variable ranking across five importance metrics. For example, the number of intervention strategies commonly used in conservation and development deployed was consistently ranked as one of the most important variables associated with more outcomes achieved across analyses. * indicates variables not selected consistently by at least three of the five variables' importance metrics (see experimental procedures and the full ranking in the dataset[38]). LA, landscape approach.

The level of outcomes reported across domains, a surrogate measure of LAs' performance, is strongly influenced by the type of LAs (Figure 4). Hence, LAs with a sectoral lens are more likely to fall short in achieving multiple outcomes, since these reported significantly fewer outcomes, on average, for each domain (Figure 4). In contrast, integrated LAs report achieving significantly more diversified outcomes across sustainable agriculture, conservation, coordination, and livelihood domains, suggesting that these are multifunctional landscapes (Figure 4). Therefore, our data reinforces previous claims that integrated LAs make the most progress toward achieving multiple sustainable development goals.[7,21] Our data did not allow us to assess whether sectoral LAs naturally transition toward integrated LAs when time and resources are sufficient. Therefore, new tools like the Mixing Board Tool can be useful to assess LA trajectories by characterizing LAs according to selectable, scalable, and measurable attributes.[44]

Similarities and differences across LA types

We found evidence of shared tendencies across LA types. Training was the most widely used implementation mechanism across LAs, regardless of type (Figure 2H). This is a coherent finding when looking only at LAs from the LAC regional assessment.[21] Hence, our empirical data show that practitioners across regions built capacity through training potentially as a means to overcome deficits in capacity for LA leadership, systems thinking, LA implementation, stakeholder engagement, negotiation, conflict resolution, monitoring, and reporting—all central aspects of integrated LAs.[13,22,45–47] LAs need substantial and continuous investment in capacity building.[10] Gaining a deeper understanding of the role of capacity building in tandem with enabling factors on behavior and perception change across stakeholders in LAs should not be underestimated.[47]

We found that LAs invested heavily in coordination (Figure 2G), a result also found elsewhere,[21] likely owing to the multiple challenges faced in operationalizing LAs (Figure 2B).[26] For example, coordination needs are manifold and include continuously identifying and engaging with diverse stakeholders who may have divergent motivations and values.[20,22] Hence, LA leaders must negotiate competing interests, facilitate consensus on the vision and priorities, mediate power imbalances, secure sustainable funding for coordination and implementation, monitor large areas and processes, strengthen local governance capacity, and deal with incoherent, incompatible, or unsupportive policies or structures.[22] Thus, our results obtained from LA practitioners reinforce the notion that, regardless of the type, LAs require strong coordination to manage multiple and often unpredictable or "wicked" challenges and to address complex, transformative, and dynamic processes.[22,23]

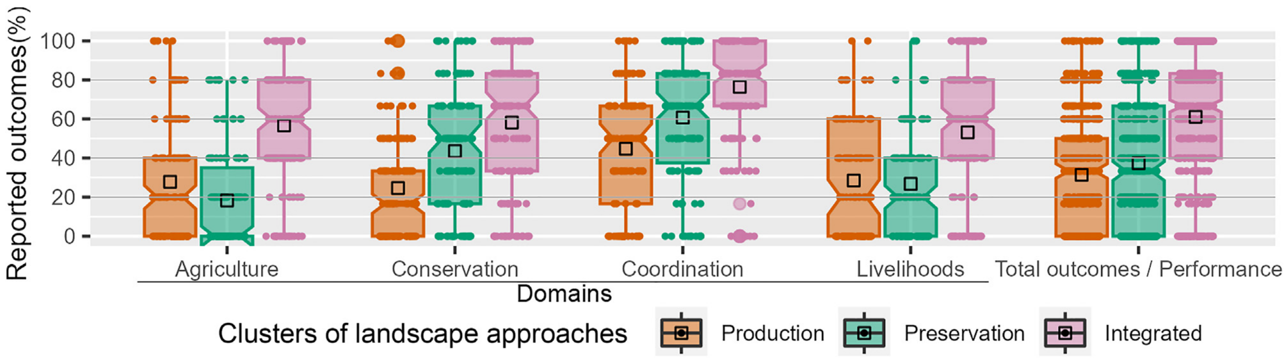

Figure 4. Self-reported outcomes used to suggest LA performance by cluster or type and across domains
The boxplot displays performance score distribution (minimum 25%, median 75%, and maximum values 100%; black squares show the mean). Each point represents an LA initiative or project, and the non-overlapping notch boxes suggest that medians differ among groups at a 95% confidence level. See Table S2 for a description of the variables.

The early inclusion and engagement of stakeholders enable transformative processes by identifying and reconciling competing values and collectively defining the shared future vision of the landscape and its inhabitants.[11,42,48] Scholars have argued that "sharing concerns and a sense of urgency" is a basic component of integrated approaches.[19] Despite the theoretical importance and need to engage sectors and stakeholders early on, we find little evidence that early engagement is widely implemented, particularly in the case of sectoral LAs (Figures 2E and 2F). This gap suggests that the time, resources, skills, and trust needed for consensus-building are potentially lacking across many LAs, common bottlenecks in LAs,[22] notably marked in sectoral LAs. For example, researchers from CGIAR and other R4D organizations report struggling to adopt or sustain multistakeholder platforms beyond project cycles in their attempts to transition from work centered on technology adoption to systems-oriented research.[39–41] This may be due to short-term funding, which rarely values the critical initial investment to engage with landscape actors as central drivers of landscape change and to sustain well-functioning multistakeholder platforms as key spaces to negotiate landscape futures in an inclusive, representative, and equitable way.[19,40,49,50]

LA longevity, inclusivity, multisectoral investments, and interventions to enable social justice associated with performance

The idea of "silver bullet" solutions to complex challenges in development and conservation agendas persists.[51–55] However, our data suggest that "how" these complex efforts are supported could be more relevant than the "what" is supported. For example, LA practitioners use diverse intervention strategies (Figure 2H). Indeed, the diversity of strategies used across LA types is highly associated with LAs' performance (Table 1). Our data also indicate that not all intervention strategies have the same impact. Across LA types, the more strategies used to enable social justice by fostering empowerment, autonomy, equity, and health, the better LAs' performance. We also found that the longer duration of the LA from its inception (LAs' longevity) and a higher total number of stakeholders involved during implementation are consistently associated with LA performance across types (Table 1). Time and inclusivity most likely contribute to less tangible to measure but central aspects of well-functioning and place-based landscape governance systems, such as improved leadership, increased justice, mediated power imbalances, established trust, and strengthened cooperation.[49,56] We acknowledge that LAs' performance can impact their longevity in that successful LAs might be able to obtain more funding and, therefore, last longer. However, our data limits testing this feedback loop (see Study limitations and caveats). LAs reporting more motivations, either because these occur in more complex contexts or because they were better characterized in the LA design, resulted in more outcomes across analyses (Table 1). Therefore, we confirm that long-term, better framed, more inclusive efforts and a diversified portfolio of actions—notably those enabling social justice—are central to LAs' performance. Perhaps, unsurprisingly, integrated LAs demonstrate this best.

Other variables associated with achieving more outcomes were relevant in certain performance analyses. For example, larger investments in intervention strategies enabling agriculture sustainability in general, and specifically through "agroecological practices," were associated with more outcomes in all analyses except in preservation LAs (Table 1). Social justice intervention strategies enabling, specifically, tenure, equity, and culture, were associated with better performance in all but production LAs (Table 1). Finally, intervention strategies aiming to support behavioral change were notably relevant in the cross-continental and preservation LAs. The remaining variables were important for one type, suggesting that their contribution to LA outcomes is context or case dependent (Table 1).

Therefore, across LA types, LAs performing better are those that last longer, are more inclusive, are better framed, and deploy a diversified portfolio of interventions. Furthermore, investing in sustainable agriculture, notably through agroecological practices, is associated with achieving more outcomes. Among the agricultural activity intervention strategies, agroecological practices, such as intensification through agroforestry, agrobiodiversity, soil conservation, and home gardens, were the most pursued to across LA types. Conversely, conventional agricultural practices, such as intensification with mechanization, fertilizers,

Table 2. Summary of the experimental procedures, variables, and tests used to respond to each research question

Research question	Method	Variables	Significance or strength tests
(1) What distinct LA types exist across continents and what are their similarities or differences?	defining clusters of LAs through multiple factor analysis (MFA) and hierarchical clustering of principal components (HCPC): (sample size for the cross-continental dataset = 357, main document and extended dataset = 380 LAs supplemental information)	124 variables from the questionnaire (question numbers 1–83 and 85–125; Table S2), excluding outcomes, total stakeholders not engaged, intervention strategies, and partner-related variables	agglomeration through Ward's method; minimizes the within-cluster variance when identifying the optimal number of clusters (Figures S1A–S1E). v test (continuous variables) and $\chi 2$ test (categorical variables) to identify variables strongly and significantly associated with each cluster (Table S3; Figures 2 and 3).
	assessing cluster accuracy through random forest/classification (sample size = 357 main document and 380 LAs supplemental information)	clusters ~124 variables from the questionnaire (question numbers 1–83 and 85–125; Table S2), excluding outcomes, total stakeholders not engaged, intervention strategies, and partner-related variables	classification error matrix showing predicted vs. actual classification (Table S1).
(2) What variables are associated with more outcomes?	identifying variables explaining LA total outcomes variance; total outcome is used as a surrogate for overall performance; analysis through random forest/regression and randomForestExplainer (four analyses conducted: one with the full cross-continental dataset (357 LAs) and one for each cluster of LAs: integrated (126 LAs), preservation (118 LAs), and production (113 LAs)	total outcomes (variable number 152, Table S2) ~103 variables from the questionnaire (question numbers 1–3, 85–88, and 157–172; Table S2), excluding outcomes per domain, total stakeholders not engaged, total actions per domain, and international partner-related questions	Consensus among five distinct metrics of variable importance: (a) number of trees, (b) minimal depth, (c) times a root, (d) node purity increase, (e) mean-squared error increase
(3) What international organizations are present or missing across LAs?	frequency of international organizations' involvement (sample size cross-continental dataset = 357 LAs)	all international organizations named in partner's theme/questionnaire (variables 153–156; Table S2)	N/A; see the full list of organizations, classification, and engagement across clusters in Table S5

and pesticides, were rarely pursued by LAs across types (Figure 2H; Table S3).

Our analyses of LAs' performance measure it as the overall or total of self-reported outcomes resulting from the LAs' efforts. The variables analyzed explained 37% of the overall outcome variability across LAs (Tables 1 and 2). Although this is a relatively high value for a cross-continental dataset that compiles information from open, complex, and diverse contexts, it also suggests that many factors beyond those captured by our questionnaire influence LA performance. For example, although 380 landscape practitioners confirm an alignment between our inclusion criteria and their landscape, we found distinct LA types, highlighting the various perceptions of what constitutes an LA. Likewise, the regional assessment questionnaire was designed to characterize LAs rather than to capture broader social and political-economic factors influencing LAs' performance. Finally, the explained variability also shows that our questionnaire design for characterizing LAs better represents preservation types, since the analyzed variables from our questionnaire explain approximately a quarter (24%) of their outcome variability (Table 1). By contrast, our questionnaire and the variables analyzed explained only 12% and 8% of the outcome variability for integrated and production LA types, respectively, indicating that a better understanding of the factors influencing the performance of these types is needed (Table 1).

Which international stakeholders are sitting at the LA table?

Our data on LA stakeholders reflect international organizations' wide interest and support of LAs across regions (268 organizations; Table S5). However, despite multistakeholder engagement being a core principle of LAs, we found limited or low levels of international stakeholder engagement (Figures 3 and 5). Of the different organization types, development agencies were the most commonly engaged across LA types and were represented across all regions (Figure 5A; Table S5). Conservation organizations were more commonly involved in preservation and integrated LAs (Figure 5A), mostly in Africa and Asia (Figure S2). United Nations organizations were also common across types and regions, whereas R4D organizations were more commonly involved in production LAs (Figure 5A; Table S4). When looking at individual organizations, their percentage of engagement in LAs remains low (Figure 5B). Only the World Wildlife Fund (WWF) (preservation LAs), Global Environment Facility (GEF) (preservation and integrated LAs), and the United Nations Development Program (UNDP) (in three clusters) were involved in slightly more than 10% of the LAs (Figure 5B). We found that

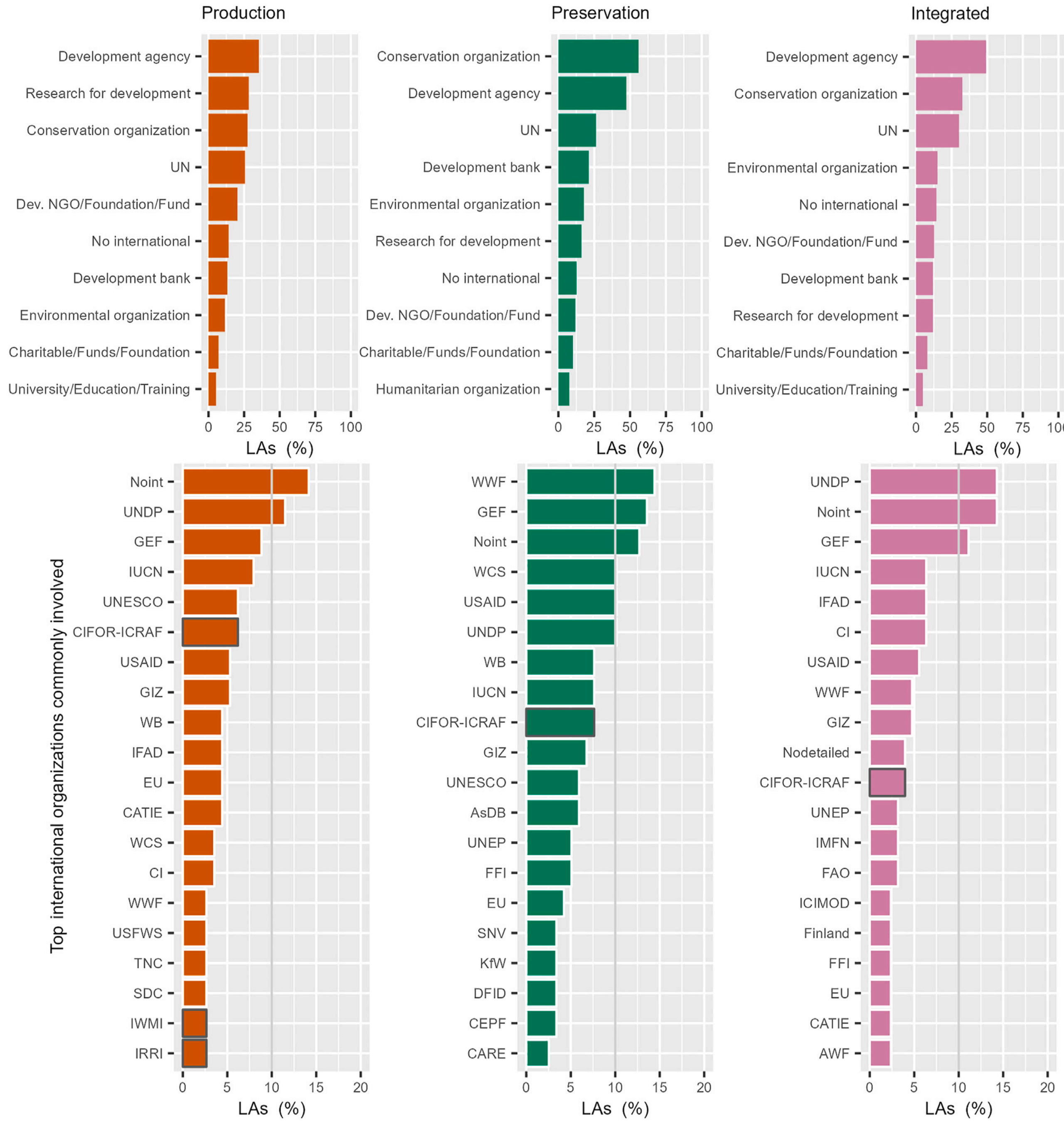

Figure 5. Top international groups and individual organizations partnering with different LA types

Shown are the top 10 international organization types (A) and top 20 unique international organizations (B) partnering on the implementation of LAs. The data source is color differentiated, and CGIAR centers have a dark outer line in (B). AsDB, Asian Development Bank; AWF, African Wildlife Foundation; CARE, Cooperative for Assistance and Relief Everywhere; CATIE, Tropical Agricultural Research and Higher Education Center; CEPF, Critical Ecosystem Partnership Fund; CI, Conservation International; CIFOR-ICRAF, Center for International Forestry Research and World Agroforestry, CGIAR; DFID, UK Department for International Development; EU, European Union; FAO, Food and Agriculture Organization of the United Nations; FFI, Fauna & Flora International, GEF, Global Environment Facility; GIZ, Gesellschaft für Internationale Zusammenarbeit; IFAD, International Fund for Agricultural Development; IUCN, International Union for Conservation of Nature; IMFN, Ibero-American Model Forest Network; IRRI, International Rice Research Institute, CGIAR; IWMI, International Water Management Institute, CGIAR; KfN, Kreditanstalt für Wiederaufbau; No int, no international organizations are involved; not detailed, specific names or acronyms were not listed, only general categories (e.g., international non-governmental organizations [NGOs]); SDC, Swiss Agency for Development and Cooperation; SNV, Stichting Nederlandse Vrijwilligers; TNC, The Nature Conservancy; UNDP, United Nations Development Program; UNEP, United Nations Environment Program; UNESCO, United Nations Educational, Scientific and Cultural Organization; USAID, United States Agency for International Development; USFWS, United States Fish and Wildlife Service; WB, World Bank; WCS, Wildlife Conservation Society; WWF, World Wildlife Fund. See Table S5 for the full list of international organizations.

33 international organizations were involved across the three LA types, confirming that the same organization can operationalize LAs differently (Figure 5; Table S5).

Despite the potential of LAs to contribute to human health and nutrition and the wide range of partners listed, we did not find international health organizations listed as partners across LA types (Table S5). Aspects contributing to human health, like food security—one intervention strategy enabling social justice—represented one of the lowest investments across LA types and, most notably, within sectoral LAs (Figure 2H; Table S3). Our findings show, for instance, that partnerships with health organizations and professionals are missing in LAs and represent an untapped potential for linking LAs to the planetary health agenda and for incorporating nutrition-sensitive (access to healthy foods), health-sensitive (pollution reduction), or zoonotic disease risk (OneHealth) interventions in LAs.[57–61]

Besides human health, LAs can also greatly contribute to the overall well-being of landscape inhabitants, particularly of the farmers, herders, fisherfolk, and forest communities who are landscape stewards (e.g., Carmenta et al.61 and Hanspach et al.[62,63]). Implementing holistic, systems-driven, and locally driven LAs has a higher positive impact on local constituents' well-being compared to single-sector style LAs, which tend to report fewer positive and more negative outcomes.[62] Therefore, given that farmers lead suicide and depression rates in countries where statistics for this issue exist, and where conventional agricultural models dominate,[64–69] assessing the comparative advantage of integrated LAs on farmers' well-being beyond subsistence or income-related aspects is both a critical necessity and an opportunity for tackling this often overlooked yet globally prevalent phenomenon.

Another stakeholder group in our dataset with low or limited engagement is the private sector, despite its considerable influence on landscape dynamics, social equity outcomes, biodiversity, and revenues.[12,70] For example, foreign agribusiness; extractive industries such as mining, oil, or gas; or forestry industries were largely absent across LA types and engagement stages (>80% LAs; Figure 3). Both international and in-country agribusinesses rarely participated in LAs, specifically in sector-focused production and preservation LAs. Only integrated LAs worked more frequently with this sector (~30% of integrated LAs) (Figure 3). The low number of international private-sector organizations listed as LA partners confirms the private sector's poor direct engagement. For example, less than 10% of the LAs in each type reported engaging with companies or corporations. However, their indirect engagement through their charitable foundations or funds was slightly higher (<13%) (Figure 5A; Table S5). Some other LA reviews indicate a common direct involvement of international companies and corporations.[35] More recently, business coalition partners (e.g., One Planet Business for Biodiversity [OP2B] or Forest Positive) are adopting LAs,[71,72] and efforts to connect landscape practitioners with investors have recently begun (e.g., Landscape Finance Lab). Still, multiple sources found null or low involvement of the private sector in LAs, which aligns with our findings.[11,22,36,45,73]

Regardless of current private sector engagement in LAs, this stakeholder could play a key role and contribute to LAs' success by connecting them with markets and finance opportunities for sustained funding and innovation.[9,19,20,74] Private-sector parties could benefit from engagement in LAs by enhancing the stability of key geographies for their value chains, reducing reputational and operational risks, and improving compliance with standards, consumers' demands, and global agreements (e.g., zero deforestation).[20,35,36,74]

While engaging the private sector in LAs can present benefits, engagement can also reinforce conflicts of interest and perpetuate entrenched positions in contradiction with local values or views. As such, private-sector engagement can increase or reinforce power imbalances and jeopardize communities' sovereignty, autonomy, and overall social and environmental justice in the landscapes in which they engage.[20,75] LA practitioners have consistently highlighted challenges in reversing power imbalances and addressing external pressures or threats to their landscapes.[10,17,20,47] Past experiences show that the private sector's motivations beyond sectoral or short-term economic objectives are often insufficient to engage in LAs.[36,74] Shifting private sector actors toward long-term engagement and equitable access/benefit-sharing goals is challenging.[45] Although meaningful partnerships and collaborations can exist when the private sector's interests align and parties commit to ongoing engagement,[74,76] a fruitful and just engagement in LAs will also require a stronger demand, accountability, and legal compliance tailored to different types of private sectors.[36,74]

Conclusion

LAs can be and ougth to be more central in achieving multiple global agendas, including the Sustainable Development Goals and Kunming-Montreal Global Biodiversity Framework.[77] To do so, the increasing support toward these complex and dynamic processes should be tailored to enhance how the most integrated LAs are being operationalized, and to support those more sectoral approaches to continue developing their cross-sectoral connections, local relevance, stakeholder engagement, and landscape-level outcomes. Despite confirming the existence of distinct LA types, we also found shared challenges hindering their performance and persistence. For example, across types, the investments in and role of capacity building and coordination in LAs should not be underestimated. Likewise, early stakeholder engagement is theoretically acknowledged but lacking in practice; hence, understanding how to pass from theory to practice is critical for LAs' performance. Our results point out time and inclusion as key aspects of better-performing LAs. Hence, more attention is needed to measure intangible and difficult-to-measure core components of LAs enabled through time and inclusion, such as trust, leadership, justice, power dynamics, and cooperation. Finally, LAs seem to benefit more from diversified portfolios of intervention strategies, especially those that enable social justice. Regarding gaps from the LAs in the cross-continental dataset, we confirm that certain key stakeholders can engage more in LAs (e.g., private sector and R4D). However, how to ensure that their short-term engagement and sectoral interests propel rather than undermine locally driven stakeholder efforts pursuing justice and sustainability in multifunctional landscapes remains an open question and requires collectively learning from past errors.[78–82] Overall, evidence shows the importance and need of putting agency and justice[83–87] at the center of international support, so it helps LAs thrive. Finally, LAs' impact and contributions to human health and overall well-being are missing or poorly documented, opening new and promising lines of research and interventions. The growing interest and support for LAs is promising. We hope our findings will enhance current efforts and research aiming to support well-functioning and lasting LAs.

EXPERIMENTAL PROCEDURES

Characterization and selection of LAs in the cross-continental dataset

The cross-continental dataset includes 357 LAs identified through regional assessments focused on and implemented in LAC, Africa, and Asia between 2012 and 2015.[16–18] LAs implemented in Europe were also characterized[25]; however, the European questionnaire was different, placing a larger emphasis on cultural heritage and values, which hindered integrating data collected for other regions. The authors of the LAC, Africa, and Asia regional assessments pre-identified potential LAs through practitioner networks and through an online search (see original articles for more details). The inclusion criteria for pre-identifying LAs were "projects, programs, platforms, initiatives or sets of activities that (1) explicitly seek to improve food production, biodiversity or ecosystem conservation and rural livelihoods; (2) work at a landscape scale and include deliberate planning, policy, management, or support activities at this scale; (3) involve inter-sectoral coordination or alignment of activities, policies, or investments at the level of ministries, local government entities, farmer and community organizations, NGOs, donors, and/or the private sector; and (4) are highly participatory, supporting adaptive, collaborative management within a social learning framework."

After the LAs were pre-identified, local landscape leaders or managers were invited to complete an online questionnaire that started by listing the inclusion criteria mentioned above. The respondent was asked to respond to the questionnaire if their project, program, or activities aligned with the criteria listed. The questionnaire was designed to characterize LAs in terms of longevity (years since inception), land uses where initiatives take place, landscape management options used, motivations that drove their creation, stakeholders and sectors engaged and at what stage (i.e., design, intervention, or both), actions carried out by the initiative, and attributable outcomes achieved by the LA.

Characterization and selection of LAs in the extended dataset

In 2021, we used the same method, questionnaire, and LA inclusion criteria as for the regional assessments to capture CGIAR's and its partners' wider engagement in LAs. We identified LAs with CGIAR engagement across the 13 CGIAR centers in two steps. First, we identified researchers working within LAs before identifying and characterizing CGIAR LAs. We contacted 986 of the 3,169 CGIAR researchers listed in the institutional directory in 2021. Contacted researchers were selected as follows: 406 were tagged in the CGIAR expert finder with the keyword "landscape," and 580 were randomly selected across the 13 CGIAR centers to guarantee contacting >30% of the research staff in each center. We contacted researchers to (1) learn about their work on LAs, (2) identify landscapes where CGIAR researchers are involved, and (3) refer us to more CGIAR researchers working on LAs. Through this effort, we mapped 55 CGIAR researchers working in or with LAs. We asked them to describe their LAs through an online questionnaire intentionally similar to the regional assessments deployed in the ArcGIS123 platform (see Table S2 for the themes and questions in the questionnaire). CGIAR researchers described an additional set of 23 landscapes in 2021. Overall, the extended dataset (cross-continental + 23 CGIAR) includes 380 LAs being implemented in 69 countries across three continents (Figure 1; Table S2).[38] Results obtained using the extended dataset are presented in Tables S3 and S4.

The questionnaire was structured in three levels. First, the structure concerned themes such as motivations, actions/investments, stakeholder groups involved, sectors involved, land uses, management types created to support LAs, and others. Second, some of the questionnaire themes included questions linked to different domains. For example, motivations that led to the creation of the LAs can be linked to five domains: sustainable agriculture, conservation, livelihoods, climate change, and coordination. Third, individual responses providing information for each question are also referred to here as variables and are the most granular level of analysis. Using the same inclusion criteria and questionnaire for characterizing LAs across continents allows cross-continental comparability. However, it required some minor alignment before further analyses. This process required removing certain variables asked inconsistently across sites. One example of this inconsistency is the variable "rocky terrain, desert," which was an option for characterizing the landscape's major land uses only collected in Asia but not in Afria or in LAC. These rare inconsistencies represented 12 questions or 9% of the questionnaire. The core questions, equivalent to 122 non-calculated variables, remained the same across data sources (Table S2).

Closed-ended individual responses were converted to binary or nominal variables, with their frequencies used to create theme- or domain-level indices (Table S2). Index values were weighted by the number of questions in each domain or theme and scaled to 0–100 points to facilitate comparison (Table S2). For example, total outcome is measured as the number of outcomes reported across domains weighted equally (Table S2). Hence, higher outcome values imply more outcomes reported across domains and, therefore, higher landscape performance. Overall, the cross-continental dataset includes 104 LAs in LAC, 87 LAs in Africa, and 166 LAs in Asia. Of the 357 LAs listed, only 38 (11%) mentioned at least one of the 13 CGIAR centers in the respondent's affiliation or as a partner. This seems to be a relatively low number, given that each assessment included at least one author from the Center for International Forestry Research and World Agroforestry (CIFOR-ICRAF) or the Alliance of Bioversity and International Center for Tropical Agriculture CGIAR centers and used CGIAR research networks to identify the LAs.

In both the cross-continental and extended datasets, LAs are referred to by different names, such as watershed/basin management, biological corridor, model forest, protected, conservation, buffer area, and others. This diversity in names for LAs aligns with previous findings.[15] We used information describing LAs, not the name of the project or landscape. For example, for the clustering, we did not differentiate LAs among those called biological corridors or basins (Tables 2 and S2).

Cluster analysis to identify distinct LA types

In 2020, Carmenta et al.[21] conducted a cluster analysis on the LAs from LAC and found four distinct clusters. Two clusters tend to use a sectoral lens either focused on agriculture or conservation, and two integrated clusters either focused on "participation and legislation" or "certification and institutions."[21] Additionally, Carmenta et al.[21] proposed grouping LA actions into intervention strategies commonly used in conservation and development. Then, the authors assessed the incidence of these intervention strategies across contexts and LA performance. Intervention strategies commonly used in conservation and development are promising strategies discussed in the scientific literature. For example, agricultural activity intervention strategy refers to the types of agriculture-related activities such as agroecological practices or intensification (adapted from Rasmussen et al.[59]); Technical coupling intervention strategy refers to the strategies for fostering behavioral change, such coordination, legislation, and certification (adapted from Phalan et al.[29]). A people-based intervention strategy aims to foster empowerment, autonomy, health, and equity (adapted from Phelps et al.,[30] Duchelle et al.,[32] and Wilebore et al.[31]).

We followed and adjusted the methodology proposed by Carmenta et al.[21] to classify LA actions into intervention strategies and identify LA types clustering similar initiatives. Our methods are an exploratory analysis (see Table 2 for a summary). LA type identification through cluster analysis includes information from the questionnaire related to the initiative's duration from inception (longevity), major land uses, management, motivations driving inception, sectors and stakeholders engaged, and actions led by and attributable to the landscape efforts (Tables 2 and S2). We excluded outcomes-related variables from the cluster analysis. Also, we excluded highly correlated variables (≥ 0.8), such as the post-classified actions into intervention strategies to avoid redundancy (Figure S3). Similarly, the total number of stakeholders engaged at the national level was also highly correlated with the total number of stakeholders engaged overall; hence, we removed the latter variable (Table 2). Finally, we only included the variables shared across regions and data collection efforts, including core and calculated variables for a total of 124 variables (Tables 2 and S2).

The cluster analysis involved two steps. The first step was to remove statistical noise from potential collinearity issues in the dataset through an MFA.[88,89] An MFA handles categorical and continuous variables and balances the influence of questionnaire themes with different numbers of variables.[88,89] The second step was to conduct an HCPC analysis on the MFA results to measure the multidimensional distance among individual LAs through Ward's method, which measures the error sum of squares after merging two clusters in a bottom-up approach.[88] HCPC describes the significant effect of each variable in each cluster through the v test for continuous variables and χ^2 test for categorical variables.[88] Therefore, continuous variables with a v test value above or below 1.96 (equivalent to $p \leq 0.05$)[88] are considered significant in this analysis. Similarly, categorical variables significantly associated with each cluster are those with a χ^2 test and p degrees of freedom (variable levels) resulting in $p \leq 0.05$.[88] Strongly and significantly associated categorical variables can be dominant (i.e., present in $\geq$80 of the LAs in the cluster) or rare (i.e., present in <20 of the LAs in the cluster). We used strongly and significantly associated continuous and categorical variables to describe each cluster (Figures 2 and 3; Table S3). We labeled each cluster based on its most salient characteristics.

Finally, we tested the accuracy of the cluster groupings through an independent method—the random forest classification[90] method (clusters $\sim$124 variables; Table 2). This test estimates a cluster classification error by comparing defined clusters with MFA and HCPC against predicted clusters with random forest. Random forest classification uses a bootstrapping process to split the data randomly and repeatedly into training ($\sim$30% of the data) and testing samples ($\sim$70% of the data) to calculate the misclassification error between both samples.[90] This process is repeated 10,000 times (trees grown) to calculate the error rate or number of LAs classified in the same cluster or other clusters (Table S1).[90]

Identifying variables and intervention strategies contributing to LA performance

We used the random forest regression method (overall outcome $\sim$ variables) to assess non-linear relations among variables associated with LAs' overall performance (Table 2). This method accounts for the large number of explanatory variables in relation to the sample size.[91,92] We ran this analysis twice using the 124 variables used in the cluster analysis plus the 11 variables from the post-classified investment strategies (162 variables in total) and replacing actions with the post-classified investment strategies to explore the incidence of these variables related to commonly used strategies in development and conservation. Both analyses rank variables similarly (Table 1). The main difference is that, when running actions and investment strategies, both highly correlated variables. For example, total intervention strategies (%) and total number of actions invested appear ranked as the first and second most important. Therefore, we ran the analysis only with investment strategies to avoid redundant variables in the ranking. We used randomForestExplainer and considered five independent importance metrics measuring the contribution to each variable to explain the total self-reported outcome variance.[93] The importance metrics evaluate variable importance differently, such as the number of nodes where the variable was selected to split the node, mean minimal depth where the variable is used to split the tree, times a variable is used to split the root node, node purity increase (reduction in the sum of the squared error after splitting a node with a variable), and mean-squared error increase after a variable is permuted.[93] All metrics capture different variable contributions or importance in explaining outcome variance.[93] We shortlisted variables based on two criteria: first, variables with the lowest average ranking across importance metrics where the lowest values indicate higher importance and second, variables shortlisted as the top 10 most important in at least three of the five independent importance metrics.

Identifying international organizations present or missing across LAs

We screened for partner organizations in three sections of the questionnaire: respondents' institution, partners inside the landscape, and partners outside of the landscape (Tables 2 and S2). We searched and verified each organization's name and recorded international partners. When respondents provided only an acronym, we searched the internet for the acronym in tandem with the name of the landscape and country. We assigned broad categories for organizations based on the description given on the organization's official webpage. Because we could not find an official page for five organizations, we used information from other sources such as Wikipedia or LinkedIn (Table S5). In certain cases, where we could not find the organization or category, we tagged projects as "unclear" (Table S5). We used descriptive statistics to describe the frequency of individual or groups of international organizations engaged across LAs types. All the analyses were conducted in R and included multiple packages.[94]

Study limitations and caveats

Our research contains the same limitations highlighted in the regional assessments and previous attempts to identify LA types through cluster analysis in LAC.[3,16–18] First, the search for projects employing an LA was based on an internet search and practitioners' international networks (e.g., CGIAR centers), which may exclude grassroots-led initiatives without an internet presence or access. The questionnaire was made available to respondents online or via email. Second, responses were given by the LA project leader or manager as only one person, self-reporting. However, it was considered that this person may be biased toward reporting more, in an attempt to convey overperformance, or may indeed report fewer investments and outcomes due to incomplete knowledge of the initiative if the practitioner was new to the position. Third, investments and outcomes are self-reported, present/absent data types. The data does not include the level of effort, time, resources, or outcome reached and/or other information validating outcomes from a third party. Fourth, the questionnaire was designed to take a snapshot of the LA projects rather than to gather a detailed description; thus, it may exclude certain activities, such as access to credit; certain outcomes, such as non-material subjective and relational ones; or impacts, such as, for instance, discerning how these outcomes affected the different stakeholders. Fifth, and last, the questionnaire is a one-time snapshot, which does not include key information on trajectories and historical legacies in each landscape. Despite these caveats, this is the largest dataset across continents systematically describing LAs. It offers a rich starting point to better understand and analyze LAs as described and operationalized by practitioners.

RESOURCE AVAILABILITY

Lead contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Natalia Estrada-Carmona (n.e.carmona@cgiar.org).

Materials availability

This study did not generate new unique materials.

Data and code availability

The extended dataset with LAs can be downloaded from Dataverse.[38] Scripts can be made available upon request.

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AUTHOR CONTRIBUTIONS

N.E.-C. developed the methodology, conducted the formal analysis and data curation, and wrote the original draft. R.C. and J.R. contributed to the development of the methodology. J.M., A.K.H., N.E.-C., F.D., and C.Z. contributed to the original study design and data collection in LAC, Africa, and Asia. All authors contributed to the conceptualization of the research and reviewed and edited the original draft.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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