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RESEARCH

Spatial Decision Support for Controlled Environment Agriculture in Cold Regions: Evidence from Alberta, Canada

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Abstract
Cold-region food systems face spatial planning constraints arising from long winters, short frost-free periods, seasonal variability, uneven infrastructure access, and land-use restrictions. Controlled-environment agriculture (CEA) can support year-round production, but its expansion depends on the alignment of suitable land, infrastructure, terrain, environmental conditions, and regional connectivity. This study develops a provincial-scale geographic information system (GIS)-based screening and planning-priority framework to delineate eligible land, compare relative suitability, and identify candidate areas for further CEA planning and investigation in Alberta, Canada. The framework applies exclusionary land-use and physical-constraint masks, followed by a multi-criteria assessment integrating infrastructure accessibility, environmental conditions, terrain limitations, and regional connectivity. Results show that development potential is highly uneven. Only 36.64% is eligible; under the baseline five-class equal-interval classification, High and Very High planning-priority areas cover 5.99% of Alberta. These areas are concentrated mainly in central and southern Alberta, with the South Saskatchewan, North Saskatchewan, and Red Deer planning regions containing 88.60% of all High and Very High priority land. The framework identifies areas warranting further planning review; it does not determine final facility locations, development allocations, or project approvals. Benchmark facilities generally scored higher than random eligible points, suggesting that infrastructure and accessibility are associated with their spatial distribution. Robustness analyses show that class-specific area totals vary across classification methods, while broad regional patterns remain stable across methods and weighting configurations. The findings show that effective CEA expansion requires a coordinated regional planning approach that aligns infrastructure investment with land-use policy and broader food-system adaptation goals.

Keywords Controlled environment agriculture · Spatial planning · Suitability analysis · Land-use policy · Cold-region food systems · Alberta

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Introduction

Food-system resilience in cold regions is strongly shaped by geographic conditions. Long winters, short growing seasons, marked intra-annual climate variability, and the often considerable distance between production areas and consumption centers limit the ability of conventional open-field agriculture to provide a stable and diversified food supply throughout the year (Linderholm, 2006). In these settings, the challenge is not only agronomic but also spatial. Food availability depends on where production can be sustained, how efficiently perishable products can reach markets, whether energy and water infrastructure can support climate-controlled cultivation, and how land-use constraints and environmental risks are distributed across space. In this context, controlled environment agriculture (CEA), including commercial greenhouses, vertical farms, and plant factories, has emerged as a promising option for strengthening year-round food production in cold regions (Gómez et al., 2019; Engler & Krarti, 2021). By regulating temperature, light, humidity, and other growing conditions, CEA reduces direct dependence on outdoor climate and allows cultivation to continue under conditions that would otherwise limit conventional agriculture (Gómez et al., 2019). Its importance, however, extends beyond production intensification alone. In cold-region settings, CEA can help shorten supply chains, improve the freshness and reliability of food supply, reduce seasonal vulnerability, and enhance broader food-system resilience. At the same time, CEA is highly sensitive to location (Engler & Krarti, 2021). Its feasibility depends on proximity to population centers and transportation corridors, access to affordable and reliable energy, terrain suitable for facility construction, water availability, and the regulatory and environmental conditions that shape land use and infrastructure expansion (GoA, 2018, 2020, 2023). Thus, while CEA reduces climatic constraints on cultivation, it also increases dependence on a wider set of locational conditions, making site selection a central planning issue rather than a secondary operational consideration (Ng et al., 2026). For this reason, the development of CEA in cold regions should be understood as a spatial planning and regional resource-allocation problem involving the organization of production, infrastructure, resources, and access (Glaros et al., 2026). This challenge has become more pressing under three concurrent pressures. First, climate variability is increasing uncertainty in seasonal production and reducing the reliability of conventional cropping calendars (Liu et al., 2026). Second, rising transportation and energy costs are reshaping the geography of food provision, particularly in regions that rely on long supply chains for fresh produce (Hossain & Kashem, 2025). Third, governments and local communities are placing growing emphasis on food security, import substitution, and the regionalization of essential supply systems (Stiles et al., 2025). Hence, these pressures raise a central planning question: where are the most suitable candidate areas for CEA facilities in cold regions when all relevant constraints are considered together? Answering this requires more than identifying climatically favorable sites, because CEA feasibility is shaped by the spatial interaction of multiple constraints that determine overall development potential (Li et al., 2025, 2026).

Recent literature has increasingly recognized that CEA is not only a technological production system but also a spatial planning problem shaped by accessibility, infrastructure, energy demand, logistics, and regional development priorities (Dohlman et al., 2024; Pereira et al., 2024; Boyd et al., 2025; Mills, 2025). In parallel, spatially explicit research on agricultural systems, ecosystem services, and land-use zoning has advanced substantially, demonstrating the value of integrated geospatial frameworks for evaluating farming functions, socio-ecological trade-offs, and policy-sensitive land allocation under changing environmental conditions (Wu et al., 2025; Huan et al., 2025; Xiong et al., 2025; Zhang et al., 2025). Geographic information systems (GIS) and multi-criteria decision analysis (MCDA) are well established in land-suitability evaluation and site selection, including agricultural and regional planning applications (Malczewski, 2006; Romano et al., 2015; Akıncı et al., 2013). Within this broader family of methods, GIS-MCDA combined with the Analytic Hierarchy Process (AHP) has been widely used to structure complex decision problems, assign criterion weights, and generate spatial suitability maps (Malczewski, 2006; Akıncı et al., 2013; Yalew et al., 2016). These approaches have supported agricultural land assessment, peri-urban and urban agriculture planning, and a wide range of spatial facility-siting problems (Ustaoğlu et al., 2021; Yalew et al., 2016). However, most existing applications remain oriented toward conventional agriculture or local-scale land allocation, with comparatively limited attention to the distinctive locational logic of CEA. This is a substantive limitation because CEA differs from open-field agriculture in its strong dependence on built infrastructure, reliable energy supply, transportation connectivity, labour access, and proximity to markets. A site that is biophysically suitable for agriculture may therefore remain operationally unsuitable for greenhouse or plant-factory development if it is poorly connected to utilities, roads, population centres, or supply-chain networks (Dohlman et al., 2024; Pereira et al., 2024). Moreover, much of the existing GIS-MCDA suitability literature has been designed for parcel, municipal, or peri-urban site selection (Akıncı et al., 2013; Ustaoğlu et al., 2021). While such studies are valuable for local decisions, they provide weaker support for regional coordination and provincial planning, where the task is not simply to identify suitable sites within a bounded study area, but to compare broad territories, evaluate uneven accessibility and development intensity, and prioritize regions for long-term investment (Yalew et al., 2016; Wu et al., 2025; Xiong et al., 2025). This limitation is particularly important for cold-region CEA, where policy discussions often take place at regional or provincial scales and involve strategic questions of infrastructure corridors, investment sequencing, and food-system resilience rather than only parcel-level siting. Many suitability studies also rely on weighted-overlay procedures without clearly distinguishing between hard exclusionary constraints and graded suitability factors, even though these play fundamentally different analytical roles (Malczewski, 2006; Yalew et al., 2016). In practice, some conditions act as absolute limits: protected areas, water bodies, incompatible land uses, or severe terrain constraints may render development infeasible regardless of any compensating advantages (Malczewski, 2004). Other conditions operate as continuous influences, including access to roads, utilities, labour pools, markets, and climatic burdens such as heating demand, which shape the relative competitiveness of otherwise feasible locations (Mills, 2025). When these two categories are conflated, suitability maps may overestimate the practically developable land base and underrepresent the real trade-offs relevant to implementation. Provincial-scale evidence on the spatial suitability of CEA in Alberta remains limited, despite the province's strong agricultural base, cold-climate conditions, and current policy support for greenhouse and vertical-farming expansion (GoA, 2026; AAFC, 2025). At the same time, recent work in China and elsewhere has generated sophisticated spatial analyses of cultivated-land functions, ecosystem-service zoning, and land-use sustainability, yet transferable frameworks that explicitly integrate CEA suitability with infrastructure dependence and regional planning remain underdeveloped (Wu et al., 2025; Xiong et al., 2025; Zhang et al., 2025). Consequently, policymakers still lack a robust provincial-scale framework capable of screening out infeasible land, ranking feasible areas under cold-region operating constraints, and comparing planning priorities across different cold-region geographies. Addressing this gap is important not only for improving site selection, but also for repositioning CEA as a strategic component of regional food-system planning rather than a purely local or facility-level intervention.

This study addresses these gaps by developing a provincial-scale GIS-based screening and planning-priority framework for CEA development under multiple boundary conditions in Alberta, Canada. The framework is intended as a spatial decision-support tool rather than as a purely descriptive mapping exercise. It first delineates land that is unavailable or unsuitable under explicit boundary conditions, thereby defining a realistic eligible land base, and then evaluates the remaining land through a multi-criteria planning-priority assessment integrating infrastructure accessibility, topographic feasibility, and climate-related conditions relevant to CEA operations. In this context, the study aims to identify eligible land, compare relative spatial suitability, and identify candidate areas for further regional and local investigation. It does not determine final facility locations, facility numbers, development allocation, project approval, or whether high-priority areas should automatically be developed. Alberta provides a compelling empirical setting because it combines strong agricultural capacity with cold-climate constraints, uneven infrastructure distribution, and large regional differences in development conditions. Although the empirical analysis is focused on Alberta, the framework is designed to offer broader methodological relevance for CEA planning in other cold-region contexts. Table 1 summarizes the main literature gaps identified in this study and shows how the proposed framework addresses them.

The remainder of the paper is organized as follows. Section "Materials and Methods" describes the materials and methods, including data sources, masking procedures, suitability assessments, and model evaluation. Section "Results" presents the GIS-based results, along with sensitivity analysis and benchmark comparisons. Section "Discussion" discusses the model's key findings, highlighting its novelty, transferability to other cold regions beyond the Alberta case, as well as its limitations and directions for future research. Finally, Section "Conclusion" concludes the paper with key insights and implications.

Materials and Methods

This section describes the spatial policy-screening framework used to evaluate CEA development priorities in Alberta. Section "Study Area, Data, and Policy-relevant Variables" introduces the study area, input datasets, preprocessing steps, and policy

Table 1 Policy gaps and contribution of the proposed framework

Policy issue	Limitations	Implications for cold-regions	Contributions
Land availability	Land is often treated as broadly available	Protected, restricted, water-covered, or steep land may be unsuitable regardless of infrastructure access	Defines a realistic eligible land base through hard-constraint masking
Infrastructure dependence	Suitability studies often emphasize environmental or parcel-level factors	CEA requires reliable access to energy, electricity, roads, water, services, labour, and markets	Integrates infrastructure accessibility into provincial planning priorities
Regional coordination	Many studies focus on local or municipal site selection	Provincial policy requires comparison across broad planning regions and infrastructure corridors	Evaluates CEA planning priorities across Alberta's regions
Policy prioritization	Weighted priority maps may not translate directly into planning action	Governments need to identify where investment, servicing, and support should be targeted	Links planning-priority patterns to infrastructure and land-use policy priorities
Cold-region planning	Climate is often treated as the dominant constraint	CEA reduces direct climate exposure but increases dependence on infrastructure and operating conditions	Assesses CEA through combined land, infrastructure, climate, and terrain constraints

relevance of each variable. Section "Hard-constraint Masking" describes the hard-constraint masking procedure used to define the eligible land base. Section "Planning-priority Assessment" presents the planning-priority assessment used to rank eligible land according to infrastructure accessibility, environmental conditions, and terrain suitability. Section "Model Evaluation" explains the sensitivity and benchmark-based evaluation procedures (Table 2).

Figure 1 summarizes the workflow. The process begins with input data preparation, followed by hard-constraint masking to define the eligible land base. Eligible land is then evaluated through accessibility and environmental scoring, integrated into a final continuous planning-priority score, subjected to sensitivity and robustness analyses, and compared with benchmark facility locations through a benchmark-based empirical plausibility assessment. Table 3 provides a consolidated summary of the criteria, weights, thresholds, and sensitivity or robustness configurations used in the framework.

Table 2 Input datasets, variables, and roles in the CEA spatial policy-screening framework

Category	Variable	Framework role	Type	Source
Constraint	Federal lands	Land-use exclusion	Hard constraint	(NRC, 2006)
Constraint	Protected areas	Conservation exclusion	Hard constraint	(NRC, 2006)
Constraint	Green Area lands	Conservative baseline policy-screening exclusion	Hard constraint	(NRC, 2006)
Constraint	Water bodies	Physical exclusion	Hard constraint	(Altalis Ltd., 2025b)
Constraint	Slope	Terrain exclusion and suitability scoring	Dual role	(Altalis Ltd., 2018)
Accessibility	City distance	Urban market, labour, and service access	Scored factor	(Altalis Ltd., 2025c)
Accessibility	Road distance	Transport and logistics access	Scored factor	(Altalis Ltd., 2025a)
Accessibility	Pipeline distance	Energy-infrastructure geography proxy	Scored factor	(ArcGIS Online, n.d.)
Accessibility	Powerline distance	Electricity infrastructure access	Scored factor	(Altalis Ltd., 2025d)
Accessibility	Water distance	Water-resource proximity	Scored factor	(Altalis Ltd., 2025b)
Climate	Heating-degree days	Heating-demand burden	Scored factor	(Macdonald et al., 2023)
Climate	Frost-free days	Broader climatic favourability	Scored factor	(AAFC, 2018)
Climate	GHI	Solar-radiation potential	Scored factor	(GSA, 2020)

Study Area, Data, and Policy-relevant Variables

Alberta is an inland province in western Canada, covering approximately 661,000 km^2 (GoA, 2015). The province contains diverse physical regions, including the Rocky Mountains in the west, boreal forest in the north, and extensive grassland and parkland landscapes in central and southern areas (GoA, n.d.a). Its continental climate is characterized by cold winters, warm summers, and strong seasonal temperature variation. These conditions create clear regional differences in agricultural potential and winter production constraints (GoA, 2005, 2009).

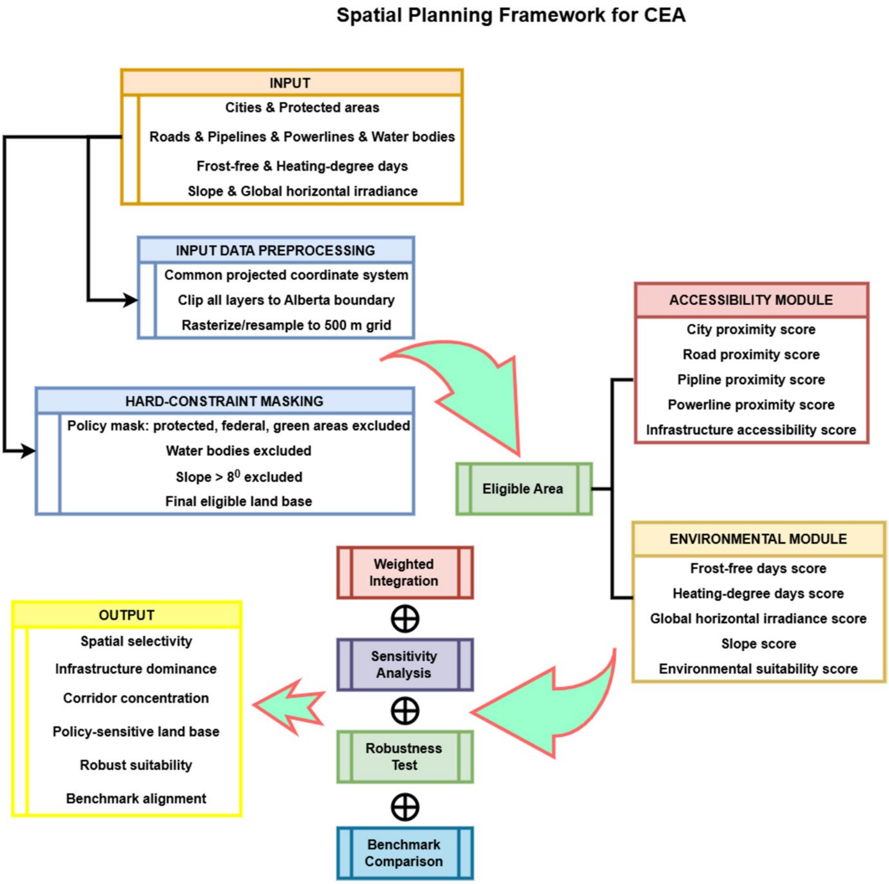

Fig. 1 Spatial policy-screening framework for evaluating CEA development priorities in cold-region land-use planning

Alberta also provides a relevant land-use policy context for CEA planning. Agricultural production is concentrated mainly in central and southern Alberta, where climatic conditions are more favourable and transportation infrastructure is better developed (GoA, 2005, 2009). Southern Alberta contains a substantial share of the province's commercial greenhouse activity, while the Edmonton–Calgary corridor is an important zone of agricultural production, urban demand, logistics, and market access (GoA, 2020, 2023). However, existing greenhouse facilities are heterogeneous and may include food-production, ornamental horticulture, nursery, and retail-oriented operations. Their spatial distribution should therefore be treated as contextual evidence rather than as a direct proxy for future food-production CEA planning. By contrast, northern Alberta is more weakly connected, more heavily forested, and more affected by land-use and accessibility constraints. Mountainous areas in western Alberta also present terrain limitations for large-scale facility development (GoA, n.d.a, 2005).

Table 3 Consolidated summary of criteria, weights, thresholds, and assumptions used in the CEA spatial policy-screening framework

Analytical stage	Criterion or configuration	Role or direction	Baseline weight or threshold	Alternative values	Key assumption
Hard-constraint masking	Federal lands; protected areas; provincial Green Area lands	Policy-screening exclusion	Excluded in baseline mask	Green Area treated as conditional in policy-mask sensitivity analysis	Broad commercial CEA promotion would require legal, jurisdictional, conservation, or land-use review beyond the provincial screening model
Hard-constraint masking	Major water bodies	Physical exclusion	Excluded	Not applicable	Water-covered cells are removed before planning-priority scoring
Hard-constraint masking	Slope exclusion	Physical exclusion	Slope $> 8°$ excluded	Not applicable	Steep terrain is screened out at the provincial scale
Accessibility scoring	City proximity	Higher score with stronger urban market, labour, and service access	0.267	AR1: 0.300; AR2: 0.280; AR3: 0.380	City proximity represents support from Tier 1 and Tier 2 urban centres
Accessibility scoring	Road proximity	Higher score with stronger transport and logistics access	0.107	AR1: 0.100; AR2: 0.150; AR3: 0.140	Road proximity is a supporting logistics factor
Accessibility scoring	Pipeline proximity	Higher score with stronger energy-infrastructure proximity	0.427	AR1: 0.350; AR2: 0.250; AR3: 0.200	Pipeline proximity is a screening-level proxy for Alberta's energy-related infrastructure geography, not a direct connection-feasibility measure
Accessibility scoring	Powerline proximity	Higher score with stronger electricity-infrastructure proximity	0.167	AR1: 0.200; AR2: 0.220; AR3: 0.180	Powerline proximity represents screening-level electricity infrastructure access
Accessibility scoring	Water-resource proximity	Higher score with stronger proximity to mapped water-related features	0.033	AR1: 0.050; AR2: 0.100; AR3: 0.100	Water proximity is not legal or physical water availability and requires follow-up review
Climate scoring	Heating-degree days (HDD)	Reverse-standardized; lower heating demand is more favourable	0.731	Not applicable	Heating demand is the dominant climatic operating burden in a cold-region greenhouse context
Climate scoring	Global horizontal irradiance (GHI)	Higher solar radiation is more favourable	0.188	Not applicable	Solar conditions contribute to operating-climate suitability
Climate scoring	Frost-free days (FFD)	More frost-free days are more favourable	0.081	Not applicable	FFD remains relevant but less decisive for controlled-environment production

Table 3 (continued)

Analytical stage	Criterion or configuration	Role or direction	Baseline weight or threshold	Alternative values	Key assumption
Environmental scoring	Climate suitability; slope suitability	Higher environmental suitability with stronger climate and terrain conditions	Climate: 0.857; slope: 0.143	Not applicable	Climate suitability dominates the environmental module, while retained slope values refine terrain feasibility
Environmental scoring	Slope suitability within retained land	Higher score for flatter retained land	0–3°: 100; > 3–6°: 50; > 6–8°: 10; > 8°: excluded	Not applicable	Slope has a dual role as an exclusion threshold and a graded suitability factor
Top-level integration	Infrastructure accessibility; environmental suitability	Weighted integration into continuous planning-priority score	S4 (Baseline): 0.75 / 0.25	S1: 0.55 / 0.45; S2: 0.60 / 0.40; S3: 0.667 / 0.333; S5: 0.85 / 0.15	Baseline reflects an infrastructure-priority policy-screening assumption
Accessibility-weight robustness	AR1, AR2, AR3	Tests sensitivity to internal accessibility weights with other modules fixed	See accessibility rows above	See accessibility rows above	Robustness assessment varies the accessibility module without changing hard constraints, environmental module, or top-level weights
Policy-mask sensitivity	Alternative Green Area treatment	Tests influence of conservative baseline policy-screening exclusion	Green Area excluded	Green Area conditional; federal lands, protected areas, major water bodies, and slope > 8° still excluded	Alternative mask tests screening assumptions and does not imply Green Area lands should automatically be developed
Developed-land footprint sensitivity	Occupied-footprint mask	Tests overlap between eligible/high-priority land and existing mapped occupation	Original eligibility mask retained as baseline	Road, established urban/rural/country residential, and mapped industrial footprints removed from baseline eligible area	Provincial-scale area-based sensitivity test, not a parcel-level land-availability assessment or complete developed-land exclusion
Classification-method robustness	Equal interval, equal area, natural breaks	Tests sensitivity of upper planning-priority classes to classification method	Five-class equal interval	Five-class equal area and five-class natural breaks	The continuous score surface is unchanged; only post-processing class thresholds vary

From a planning perspective, Alberta is also governed through a multi-level land-use system in which provincial regional planning, municipal land-use regulation, infrastructure servicing, water access, and sectoral development policies interact (GoA, 2008, n.d.b). The land-use framework (LUF) regions provide a useful scale for comparing broad planning priorities across the province (GoA, n.d.c), while implementation decisions would normally require municipal zoning review, servicing-capacity assessment, utility coordination, water-access evaluation, and site-specific permitting. The framework developed in this study is therefore positioned at the provincial and regional screening stage, where its main role is to identify areas that warrant more detailed local planning, infrastructure, water-access, and permitting review.

Figure 2 shows the provincial boundary, LUF planning regions, major cities, major water bodies, and selected benchmark CEA and greenhouse facilities used for contextual comparison.

The framework combines exclusionary screening layers and scored planning-priority factors. Exclusionary screening layers represent land treated as constrained or physically unsuitable under the adopted provincial screening logic. Scored factors represent conditions that affect the relative planning priority of otherwise eligible land. This distinction is central to the policy interpretation of the framework because it separates land-use restrictions from factors that can be improved, mitigated, or prioritized through infrastructure and regional development policy.

Infrastructure-related datasets were obtained from provincial geospatial sources, including Altalis and an ArcGIS REST Feature Service for Alberta pipeline data (Altalis Ltd., 2025c, a, d, b, 2018; ArcGIS Online, n.d.). Pipeline proximity was used as a broad proxy for Alberta's energy-related infrastructure geography. The pipeline layer was not interpreted as a direct measure of service connection, available capacity, pipeline type, fuel availability, ownership access, or project-level connection feasibility. These datasets included urban centres, roads, powerlines, pipelines, and water-related resources. Euclidean distance rasters were generated for the infrastructure variables and used in the accessibility module. These variables were selected because large-scale CEA depends on transportation access, utility networks, energy-related infrastructure, water availability, labour access, service availability, and proximity to urban markets.

Climate-related variables were compiled from public data sources (Macdonald et al., 2023; AAFC, 2018; GSA, 2020). Heating Degree Days (HDD) were used to represent cumulative heating demand, Frost-Free Days (FFD) to represent broader climatic favourability, and Global Horizontal Irradiance (GHI) to represent solar radiation potential (Ahamed et al., 2019; Chen et al., 2012; Cossu et al., 2018). These variables capture the operating-climate dimension of CEA planning rather than conventional open-field agricultural suitability alone.

Several layers were used as hard constraints under the adopted provincial screening logic. The policy mask included federal lands, protected areas, and provincial Green Area lands. Provincial Green Area lands were treated as a conservative screening exclusion rather than as a universal legal prohibition, reflecting the objective of identifying near-term commercial CEA opportunities in areas with fewer land-use conflicts and stronger infrastructure alignment. The physical mask included major

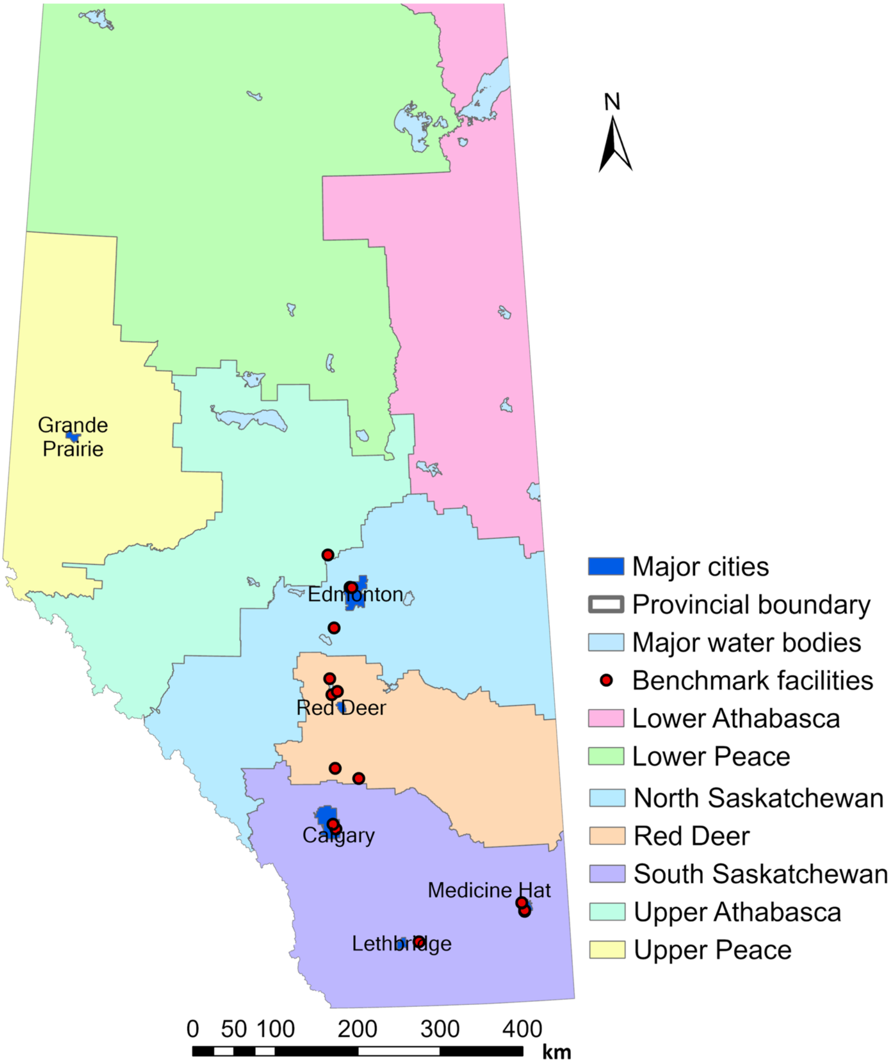

Fig. 2 Study area map of Alberta, Canada, showing the provincial boundary, LUF planning regions, major cities, major water bodies, and selected benchmark CEA and greenhouse facilities used for contextual comparison

water bodies and areas with slope values above 8°. Slope also played a dual role in the model: values above 8° were excluded, while retained values were further incorporated into the planning-priority assessment through graded scoring (Aldrich & Bartok, 1994; Everest et al., 2021).

All spatial datasets were projected to a common coordinate system, clipped to the Alberta boundary, converted to raster format, and standardized to a spatial resolution of 500 m. This resolution provides an appropriate balance between spatial detail and computational efficiency for provincial-scale planning. The standardized layers were then integrated into the workflow for constraint masking, planning-priority assessment, regional tabulation, and model evaluation.

Table 2 summarizes the datasets and their roles in the framework. Together, these inputs define a two-stage assessment. The first stage identifies the eligible land base by applying policy and physical constraints. The second stage ranks eligible land according to infrastructure access, operating-climate conditions, and terrain suitability. This structure supports policy interpretation by distinguishing land that should be excluded from land that may be prioritized, conditionally supported, or examined at finer planning scales.

Hard-constraint Masking

The first stage of the framework defined the eligible land base for CEA development by applying policy-screening and physical-exclusion criteria. These hard constraints represented conditions under which land was screened out or treated as unsuitable for near-term commercial CEA prioritization at the provincial screening scale. Unlike scored planning-priority factors, hard constraints were not evaluated as compensable trade-offs. A location screened out by these criteria was removed from subsequent planning-priority assessment regardless of its infrastructure or climate advantages.

Policy-based exclusions included federal lands, protected areas, and provincial Green Area lands. These categories do not imply identical legal status, but each represents land where broad commercial CEA promotion would require additional legal, jurisdictional, conservation, or land-use review beyond the scope of a provincial screening model. They were therefore combined into a single policy mask for the baseline configuration. Provincial Green Area lands were treated as a conservative screening exclusion, while their influence on the eligible land base was examined through a policy-mask sensitivity analysis. The baseline and alternative Green Area treatments should therefore be read as two policy-screening assumptions rather than as competing legal interpretations of land availability. Equation 1 defines the binary policy mask:

$$M_{\text{policy}} = \begin{cases} 1, & \text{available} \\ 0, & \text{excluded} \end{cases} \tag{1}$$

Physical exclusions included major water bodies and steep terrain. Major water bodies were excluded from development, and areas with slope values greater than 8° were removed as a provincial-scale screening threshold. This threshold is consistent with the general preference in greenhouse engineering and land-suitability guidance for relatively flat terrain, although many project-level recommendations prefer substantially flatter sites (Aldrich & Bartok, 1994; Akıncı et al., 2013; Everest et al., 2021). Equation 2 defines the water and slope masks:

$$M_{\text{water}} = \begin{cases} 1, & \text{outside major water bodies} \\ 0, & \text{inside major water bodies} \end{cases} \qquad M_{\text{slope}} = \begin{cases} 1, & \text{slope} \leq 8^\circ \\ 0, & \text{slope} > 8^\circ \end{cases} \tag{2}$$

The combined binary eligibility mask was obtained by intersecting the policy, water, and slope masks, as shown in Eq. 3:

$$M_{\text{eligible}} = M_{\text{policy}} \cdot M_{\text{water}} \cdot M_{\text{slope}} \tag{3}$$

Only cells with $M_{\text{eligible}} = 1$ were retained for subsequent planning-priority assessment. Thus, M_{eligible} is the combined binary eligibility mask, not the final continuous suitability or planning-priority score. In policy terms, this procedure separated land screened out under the adopted policy-screening and physical-exclusion assumptions from land retained for relative prioritization under infrastructure, climate, and terrain conditions.

Planning-priority Assessment

After the eligible land base was defined, the retained cells were ranked through a planning-priority assessment designed to support provincial-scale policy screening rather than parcel-level investment decisions. The assessment included two components: infrastructure accessibility and environmental suitability. Infrastructure accessibility represented the degree to which eligible land was connected to the systems needed for commercial CEA development, while environmental suitability represented operating-climate and terrain-related conditions. The final planning-priority score was obtained by weighted integration of these two components.

Infrastructure accessibility was evaluated using five factors: proximity to cities, roads, pipelines, powerlines, and water resources. For each factor, the non-linear distance-decay penalty function in Eq. 4 was applied so that the penalty increased with distance and asymptotically approached 100:

$$P_i = 100\left(1 - e^{-d_i/\lambda_i}\right), \tag{4}$$

where P_i is the penalty score for factor i, d_i is the Euclidean distance to the corresponding feature, and λ_i controls the decay rate. Smaller λ_i values produce more rapid increases in penalty with distance.

Euclidean distance was used as a transparent provincial-screening measure of proximity rather than as a detailed representation of network travel time, connection cost, or logistics performance. The decay parameters were therefore treated as planning-oriented settings rather than fixed empirical thresholds. In the exponential penalty function, a distance equal to λ_i corresponds to a penalty of approximately 63.2, while distances of $2\lambda_i$ and $3\lambda_i$ correspond to penalties of approximately 86.5 and 95.0, respectively. Smaller λ_i values therefore imply a more rapid loss of accessibility advantage with distance.

The factor-specific λ_i values were defined with reference to the literature, the operational logic of large-scale CEA, and the provincial context of Alberta (Deichmann et al., 2009; Iddio et al., 2020; GoA, 2020). A smaller decay parameter was used for pipeline proximity because energy-related infrastructure access was treated as more distance-sensitive in cold-region CEA planning. Larger decay parameters were used for roads, powerlines, water resources, and city proximity because these variables represent broader accessibility, service-support, and regional development conditions.

City accessibility was represented through a two-tier urban system. Calgary and Edmonton were treated as Tier 1 metropolitan centres, while Red Deer, Grande Prairie, Lethbridge, and Medicine Hat were treated as Tier 2 regional centres. Separate penalty surfaces were calculated for the two tiers, and Eq. 5 retained the lower value for each cell:

$$P_{\text{city}} = \min\left(P_{\text{city},t1}, P_{\text{city},t2}\right). \tag{5}$$

This formulation assumes that a location may benefit from proximity to either a major metropolitan centre or a secondary regional centre. City proximity was used as a composite indicator of near-urban support conditions, including market access, labour availability, business services, distribution opportunities, and operational support (Deichmann et al., 2009; GoA, 2018).

The relative importance of the five accessibility factors was determined using the Analytic Hierarchy Process (AHP) (Malczewski, 2006; Akıncı et al., 2013). In this study, AHP was used to encode an explicit planning perspective for cold-region, infrastructure-intensive CEA rather than to estimate statistical importance from observed facility locations. The AHP weights were specified as a literature-informed, author-defined baseline configuration rather than as empirically estimated stakeholder preferences, expert-elicited preferences, or statistically fitted coefficients. The pairwise comparisons reflected the assumption that pipeline proximity is especially relevant in Alberta because of the heating burden and energy geography of large-scale greenhouse production. City and powerline proximity were also given substantial importance because they represent market, labour, service, and electricity access. Road proximity was treated as a supporting logistics factor. Water proximity was assigned a relatively low weight because the variable represents only screening-level proximity to mapped water-related features, not licensed withdrawal capacity, water quality, allocation status, seasonal availability, municipal servicing capacity, or basin-level allocation constraints. Therefore, water access was not treated as fully resolved by the provincial screening model; instead, it was interpreted as a required follow-up assessment for candidate areas identified by the framework (Ahamed et al., 2019; Aldrich & Bartok, 1994; GoA, 2023). The resulting adopted weights, rounded to three decimal places from the AHP-derived priority vector, were 0.267 for city proximity, 0.107 for road proximity, 0.427 for pipeline proximity, 0.167 for powerline proximity, and 0.033 for water proximity. The accessibility matrix had acceptable internal consistency, with $\lambda_{\max} = 5.1189$, $CI = 0.0297$, and $CR = 0.0266$. These weights should be interpreted as a transparent baseline policy configuration rather than as universally fixed empirical coefficients. Accordingly, the weighting exercise is best understood as explicit policy parameterization for provincial screening rather than as causal calibration of facility-location behavior. The 16 benchmark facilities described below were not used to calibrate these weights. Their implications for spatial outcomes were examined through top-level weighting sensitivity analysis.

The weighted accessibility penalty was calculated using (6):

$$P_{\text{access}} = \sum_{i=1}^{n} w_i P_i. \tag{6}$$

Using the rounded adopted weights, the accessibility module was specified as Eq. 7:

$$P_{\text{access}} = 0.267P_{\text{city}} + 0.107P_{\text{road}} + 0.427P_{\text{pipeline}} + 0.167P_{\text{powerline}} + 0.033P_{\text{water}}. \tag{7}$$

The penalty surface was then transformed into a positive infrastructure accessibility score using (8):

$$S_{\text{access}} = 100 - P_{\text{access}}, \tag{8}$$

where higher values of S_{access} indicate stronger infrastructure accessibility.

Environmental suitability was assessed using climate suitability and slope suitability. Climate suitability was derived from HDD, GHI, and FFD (Ahamed et al., 2019; Chen et al., 2012; Cossu et al., 2018). Because these variables were measured in different units, each was normalized to a 0–100 suitability scale before aggregation. HDD was reverse-standardized because lower heating demand is more favourable for greenhouse development.

The climate weights were also determined using AHP as a literature-informed, author-defined baseline configuration. The pairwise comparisons reflected the assumption that, in a cold-region greenhouse context, heating demand is the dominant climatic operating burden, followed by solar conditions, while frost-free period remains relevant but less decisive for controlled-environment production (Nasrollahi et al., 2021; Katzin et al., 2021; Engler & Krarti, 2021). The resulting adopted weights were rounded to three decimal places from the AHP-derived priority vector. The climate matrix had acceptable internal consistency, with $\lambda_{\max} = 3.0649$, $CI = 0.0324$, and $CR = 0.0559$. The climate suitability score was calculated using (9):

$$S_{\text{climate}} = \sum_{j=1}^{m} \alpha_j S_j. \tag{9}$$

Using the rounded adopted weights, the climate module was specified as Eq. 10:

$$S_{\text{climate}} = 0.731S_{\text{HDD}} + 0.188S_{\text{GHI}} + 0.081S_{\text{FFD}}. \tag{10}$$

Slope played a dual role in the framework (Aldrich & Bartok, 1994; Everest et al., 2021). Values above 8° were excluded during the hard-constraint masking stage. Within the retained eligible land base, slope was further scored to distinguish relatively flat land from marginally feasible terrain according to Eq. 11:

$$S_{\text{slope}} = \begin{cases} 100, & 0 \leq \text{slope} \leq 3^\circ \\ 50, & 3^\circ < \text{slope} \leq 6^\circ \\ 10, & 6^\circ < \text{slope} \leq 8^\circ \\ 0, & \text{slope} > 8^\circ \end{cases} \tag{11}$$

The environmental suitability score was calculated using (12):

$$S_{\text{env}} = \sum_{k=1}^{p} \beta_k E_k. \tag{12}$$

The two-factor environmental matrix was perfectly consistent, with $\lambda_{\max} = 2.0000$ and $CI = 0.0000$. Using the rounded adopted weights, the environmental module consisted of climate suitability and slope suitability, as shown in Eq. 13:

$$S_{\text{env}} = 0.857 S_{\text{climate}} + 0.143 S_{\text{slope}}. \tag{13}$$

Finally, infrastructure accessibility and environmental suitability were integrated through the weighted linear combination in Eq. 14:

$$S = w_A S_{\text{access}} + w_E S_{\text{env}}. \tag{14}$$

The two-factor top-level matrix was perfectly consistent, with $\lambda_{\max} = 2.0000$ and $CI = 0.0000$. In the baseline configuration, accessibility was assigned a weight of 0.75 and environmental suitability a weight of 0.25, producing (15):

$$S = 0.75 S_{\text{access}} + 0.25 S_{\text{env}}. \tag{15}$$

This baseline weighting reflects an infrastructure-priority policy-screening assumption for large-scale CEA in Alberta, with environmental conditions used to refine relative priority within the eligible land base (Ahamed et al., 2019; GoA, 2020; Aldrich & Bartok, 1994). Because the component scores are expressed on 0–100 scales and the top-level weights in Eq. 15 sum to one, the continuous planning-priority score is theoretically bounded between 0 and 100 for cells retained by M_{eligible}. Its influence on the final spatial pattern was evaluated through top-level weighting sensitivity analysis. For reporting and mapping, the continuous planning-priority score was classified into five ordinal classes: very low, low, moderate, high, and very high. The classes were defined using equal-interval classification over the range of the final planning-priority raster. These classes were used for provincial and regional area summaries and should be interpreted as relative planning-priority categories rather than as regulatory zoning designations.

Model Evaluation

The framework was evaluated using top-level weighting sensitivity analysis, accessibility-weight robustness analysis, policy-mask sensitivity analysis, the occupied-footprint sensitivity scenario, classification-method robustness analysis, and benchmark-based empirical plausibility assessment. These procedures examined whether the resulting spatial priorities were robust under alternative weighting, masking, and classification assumptions and whether they were broadly consistent with the observed geography of identifiable food-production-related CEA and greenhouse facilities.

The baseline configuration (S4) was defined as $(w_A, w_E) = (0.75, 0.25)$, reflecting an infrastructure-priority planning assumption for large-scale CEA deployment in Alberta. Sensitivity analysis first examined the upper-level balance between infrastructure accessibility (w_A) and environmental suitability (w_E). Five top-level weighting configurations were constructed by varying $w_A = 0.55, 0.60, 0.667, 0.75, 0.85$, with corresponding values of $w_E = 0.45, 0.40, 0.333, 0.25, 0.15$, respectively. These configurations, denoted S1, S2, S3, S4 (Baseline), and S5, represent different planning assumptions, ranging from a more balanced infrastructure–environment perspective to a stronger infrastructure-priority perspective.

A second accessibility-weight robustness analysis varied the internal weights of the accessibility module while keeping the hard-constraint structure, environmental module, and top-level integration weights fixed. Three alternative accessibility-weight configurations were evaluated: AR1, with a mildly diversified infrastructure emphasis; AR2, with a diversified accessibility emphasis and reduced pipeline dominance; and AR3, with an urban-service-oriented emphasis and substantially reduced pipeline dependence. The corresponding weights for city, road, pipeline, powerline, and water were 0.300, 0.100, 0.350, 0.200, and 0.050 for AR1; 0.280, 0.150, 0.250, 0.220, and 0.100 for AR2; and 0.380, 0.140, 0.200, 0.180, and 0.100 for AR3. For each configuration, robustness was assessed using pixel-wise Pearson correlation coefficients, associated R^2 values, and overlap ratios for the top 10% highest-priority cells. For the top-decile overlap analysis, each final planning-priority raster was reclassified into 10 equal-area classes using the Slice tool, and the highest class was treated as the top 10% high-priority area.

Because the treatment of provincial Green Area lands represents a conservative policy-screening assumption, an additional policy-mask sensitivity analysis was conducted. In the baseline configuration, federal lands, protected areas, provincial Green Area lands, major water bodies, and areas with slope values greater than 8° were excluded. In the alternative policy-mask configuration, provincial Green Area lands were treated as conditional rather than excluded lands, while the other hard constraints remained unchanged. The purpose of this analysis was to examine how strongly the estimated eligible land base and regional planning-priority pattern depended on the conservative exclusion of Green Area lands.

Developed-land Footprint Sensitivity Analysis

The original eligibility mask was retained as the baseline provincial screening scenario. To address the possibility that existing roads, residential development, and industrial occupation could remain within the baseline eligible land base, a separate conservative occupied-footprint sensitivity mask was constructed using polygon sublayers from the 2023 Alberta Human Footprint Inventory described by Alberta

Biodiversity Monitoring Institute (2026). The mask removed mapped road and transportation footprints, established urban, rural, and country residential footprints, and mapped industrial occupation categories, including facility, plant, mill, utility, tank-farm, camp-industrial, oil-and-gas, and urban-industrial footprints. Vegetated roads, winter roads, truck trails, residential clearings, and uncertain industrial clearing categories were retained because their permanent occupation or suitability status could not be established reliably at the provincial screening scale. Clearly mapped occupied footprints were removed from the baseline eligible area after the polygons were converted to a 500 m raster aligned with the existing eligibility grid.

The occupied-footprint sensitivity scenario was compared with the baseline using total eligible area, High + Very High planning-priority area, and the percentage of baseline priority land removed. This analysis is a provincial-scale robustness test of existing mapped occupation, not a parcel-level land-availability assessment, a definitive developed-land exclusion, or a replacement for the original eligibility mask. Some industrial or previously developed sites may still be relevant for vertical farming, plant factories, adaptive reuse, warehouse conversion, or building-integrated CEA, so the sensitivity mask should not be interpreted as evidence that all developed or industrial land is unsuitable for every form of CEA.

Classification-Method Robustness Analysis

To evaluate whether the upper planning-priority classes depended on the selected classification method, the continuous baseline planning-priority surface from the baseline configuration (0.75 accessibility / 0.25 environmental suitability) was reclassified using two alternative five-class methods while preserving the original raster, extent, mask, cell alignment, and 500 m resolution. The existing baseline equal-interval classification was retained as the primary reporting method. Alternative classifications consisted of an equal-area classification, equivalent to a quantile-style division of valid cells, and a natural-breaks classification based on Jenks optimization. Classes 4 and 5 were treated as High and Very High. Classification robustness was assessed using class score ranges, total High + Very High planning-priority area, regional distribution, Jaccard overlap with the baseline High + Very High set, and baseline retention. Jaccard similarity was defined as $J = |A \cap B|/|A \cup B|$, where A is the baseline High + Very High set and B is the corresponding alternative set. Baseline retention was defined as $R = |A \cap B|/|A|$, or the proportion of baseline High + Very High cells also classified as High or Very High under the alternative method.

Benchmark-Based Empirical Plausibility Assessment

In addition to sensitivity and robustness analyses, a benchmark-based empirical plausibility assessment was conducted using 16 identifiable food-production-related CEA and greenhouse facilities in Alberta. These benchmark locations were not used in model construction, weight specification, or parameter calibration. Facilities were included only when they had a clear relationship to year-round food production, including indoor CEA operations, vertical farms, and produce-oriented greenhouse operations. Facilities primarily associated with ornamental horticulture, nursery production, garden-centre retail, or other non-food greenhouse uses were not intentionally included because their locational logic may differ from food-production-oriented CEA. Benchmark locations were compiled from publicly identifiable facility information, including facility websites, business listings, municipal or regional location information, and map-based coordinate verification where available. Because the resulting dataset is not a complete inventory of all greenhouse or CEA operations in Alberta, it should be interpreted as a conservative plausibility sample rather than as a formal validation dataset. The benchmark comparison was therefore designed to test whether identifiable food-production-related facilities tend to occupy higher-scoring locations than the broader eligible land base, not to predict all existing greenhouse locations or to evaluate firm-level siting decisions.

Planning-priority scores were extracted at the 16 benchmark locations under all top-level weighting configurations. To provide an initial background comparison, 1000 unrestricted random points were generated within the eligible land base, and planning-priority scores were extracted from the same configuration rasters. The benchmark and random samples were compared using descriptive statistics, Mann–Whitney U tests, and Cliff's delta as a non-parametric effect-size measure. Because spatial dependence may violate strict independence assumptions among nearby background points, nominal Mann–Whitney p-values were retained only as descriptive results from the unrestricted comparison rather than treated as the primary inferential evidence. The benchmark comparison was therefore interpreted from the combined pattern of descriptive differences, effect sizes, and the additional spatial-thinning robustness analysis described below, not as formal predictive validation.

To examine whether local spatial dependence among background locations affected the benchmark comparison, an additional spatial-thinning robustness analysis was conducted. Incremental spatial autocorrelation of the baseline continuous planning-priority surface was evaluated at 500 m distance increments. The first local z-score peak occurred at 66 km, where positive spatial autocorrelation remained evident (Moran's $I = 0.370035$; z-score = 262.830743). The 66 km distance was therefore used as a practical minimum-separation distance to reduce local spatial redundancy rather than as an independence threshold. Ten separately generated spatially thinned background samples were created within the baseline eligible land base, each containing 50 points separated by a minimum distance of 66 km. Planning-priority scores under S1–S5 were extracted for each sample. Robustness was assessed from the ranges of background means and medians, benchmark–background mean and median differences, and Cliff's delta across the ten repeated samples.

Results

This section presents the spatial results of the CEA policy-screening framework in the same sequence as the analytical workflow. Section "Eligibility and Exclusion Results" reports the eligibility and exclusion results from hard-constraint masking. Section "Infrastructure Accessibility Pattern" describes infrastructure accessibility patterns across the eligible planning space. Section "Climate and Environmental Suitability" presents climate suitability and integrated environmental suitability. Section

"Baseline Planning-Priority Pattern" reports the baseline planning-priority pattern after weighted integration. Section "Sensitivity and Robustness Analyses" evaluates the stability of spatial priorities under alternative top-level weighting configurations, accessibility-weight robustness configurations, policy-mask assumptions, the occupied-footprint sensitivity scenario, and classification-method robustness analysis. Section "Benchmark-Based Empirical Plausibility Assessment" compares the results with 16 identifiable food-production-related benchmark facilities in Alberta.

Eligibility and Exclusion Results

The first analytical step addressed the study objective of defining a realistic provincial screening space before assigning relative planning-priority scores. After applying the hard-constraint mask, a substantial share of the province was removed from further assessment because of policy-screening exclusions, major water bodies, or slope values greater than 8° (see Fig. 3). Of the 2,642,862 raster cells in the provincial analysis area, 968,378 cells were retained as eligible, corresponding to 242,094.50 km^2 or 36.64% of the analysis area. By contrast, 1,674,484 cells, representing 418,621.00 km^2 or 63.36%, were screened out by the adopted policy-screening and physical-exclusion criteria (Table 4).

This result indicates that CEA planning priorities should not be interpreted as a simple function of Alberta's large land base. At the provincial screening scale, nearly two-thirds of the analysis area was removed before relative planning priority was assessed. The eligible land base therefore represents a constrained planning space defined by the adopted policy-screening and physical-exclusion assumptions, within which infrastructure access, environmental conditions, and terrain suitability can be compared.

Infrastructure Accessibility Pattern

Within the retained planning space, the next step evaluated infrastructure conditions relevant to larger-scale CEA development at the provincial screening scale. The accessibility surface revealed a strongly infrastructure-oriented planning pattern across Alberta (see Fig. 4).

High-accessibility areas were concentrated near major urban centres and linear infrastructure networks, especially where pipelines, powerlines, roads, and water resources overlapped. Lower scores were more common in remote parts of northern Alberta and other areas with weaker infrastructure access. Because pipeline proximity received the largest weight, followed by city and powerline proximity, the accessibility surface emphasized infrastructure-connected corridors rather than broad continuous zones. This pattern identifies areas with comparatively stronger modelled proximity to the infrastructure and urban-service variables represented in the provincial screening framework.

Climate and Environmental Suitability

The environmental component then evaluated operating-climate and terrain conditions within the same screening framework. The climate suitability surface showed a broader regional gradient than the infrastructure accessibility surface (see Fig. 5).

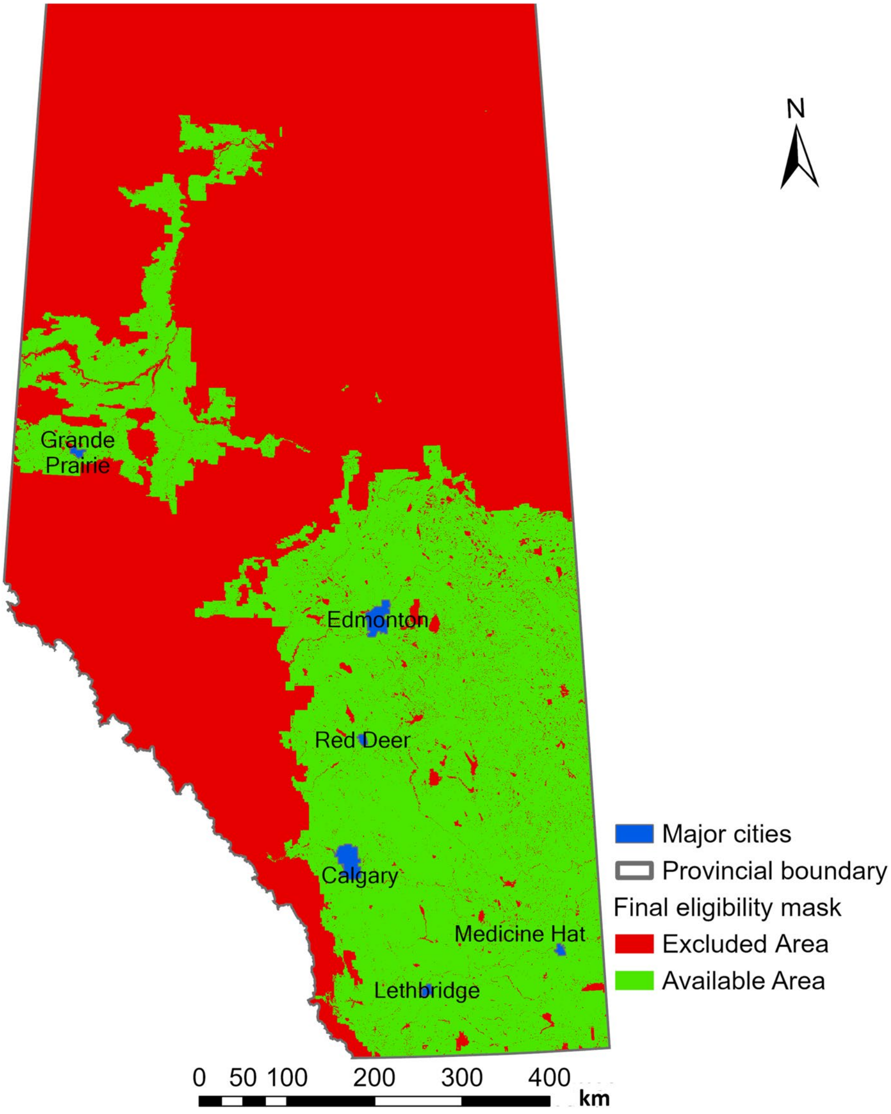

Fig. 3 Final hard-constraint mask and retained eligible land base under the adopted policy-screening and physical-exclusion criteria. Excluded or blank cells are not scored in subsequent planning-priority maps and do not represent a suitability score of zero

Areas with lower heating demand, higher solar input, and longer frost-free periods generally received higher climate scores. After slope was incorporated, the environmental suitability surface retained this broad regional pattern but became more selective in areas with less favourable terrain (see Fig. 6). Because climate received a much larger weight than slope in the environmental module, the environmental suitability surface remained primarily climate-driven.

Table 4 Cell counts, areas (km^2), and percentage shares of the provincial analysis area after hard-constraint masking

Mask category	Cell count	Area (km^2)	Provincial analysis area (%)
Eligible area	968,378	242,094.50	36.64
Excluded area	1,674,484	418,621.00	63.36
Total	2,642,862	660,715.50	100.00

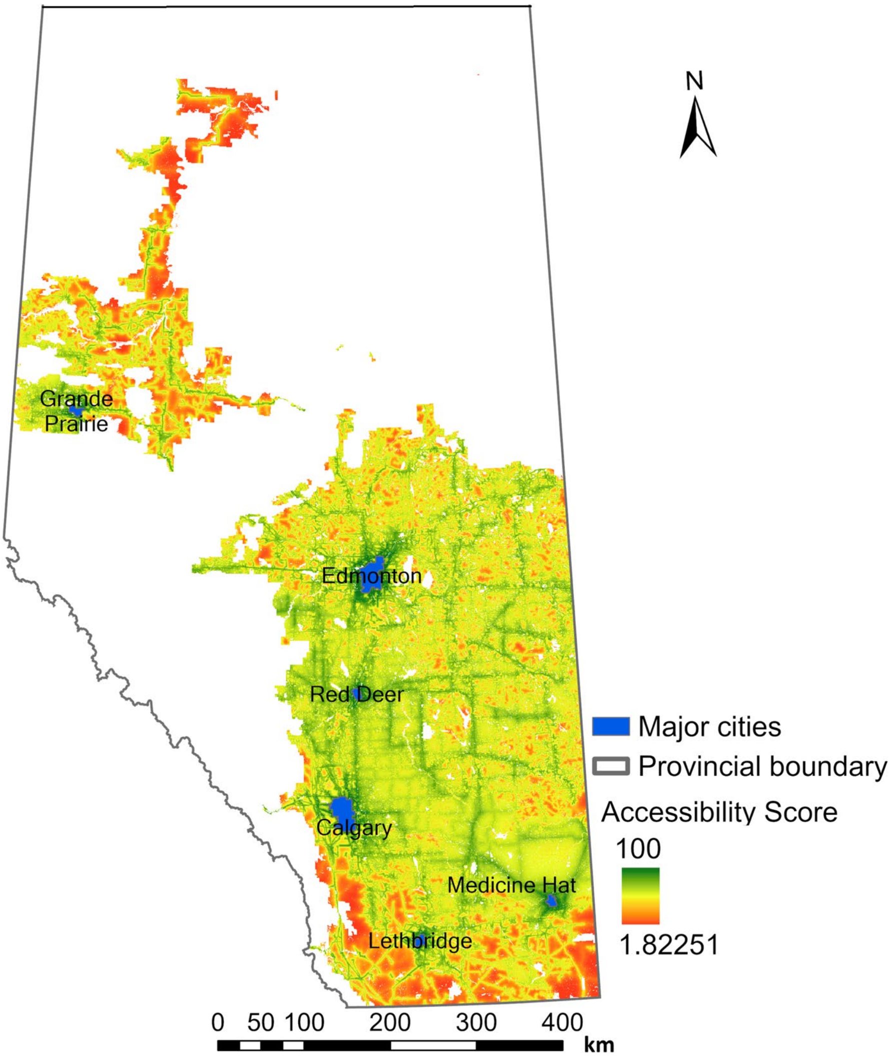

Fig. 4 Spatial distribution of infrastructure accessibility scores in Alberta. Higher values indicate stronger proximity to critical infrastructure and urban service centres. White, blank, or no-data cells are not scored and should not be interpreted as accessibility scores of zero

Baseline Planning-Priority Pattern

The baseline configuration integrated infrastructure accessibility and environmental suitability to compare relative planning priorities within the eligible land base. It revealed a spatially selective pattern of CEA planning priorities across Alberta (see Fig. 7).

Within the retained eligible area, the highest priority values were concentrated in locations that combined strong infrastructure access with acceptable environmental

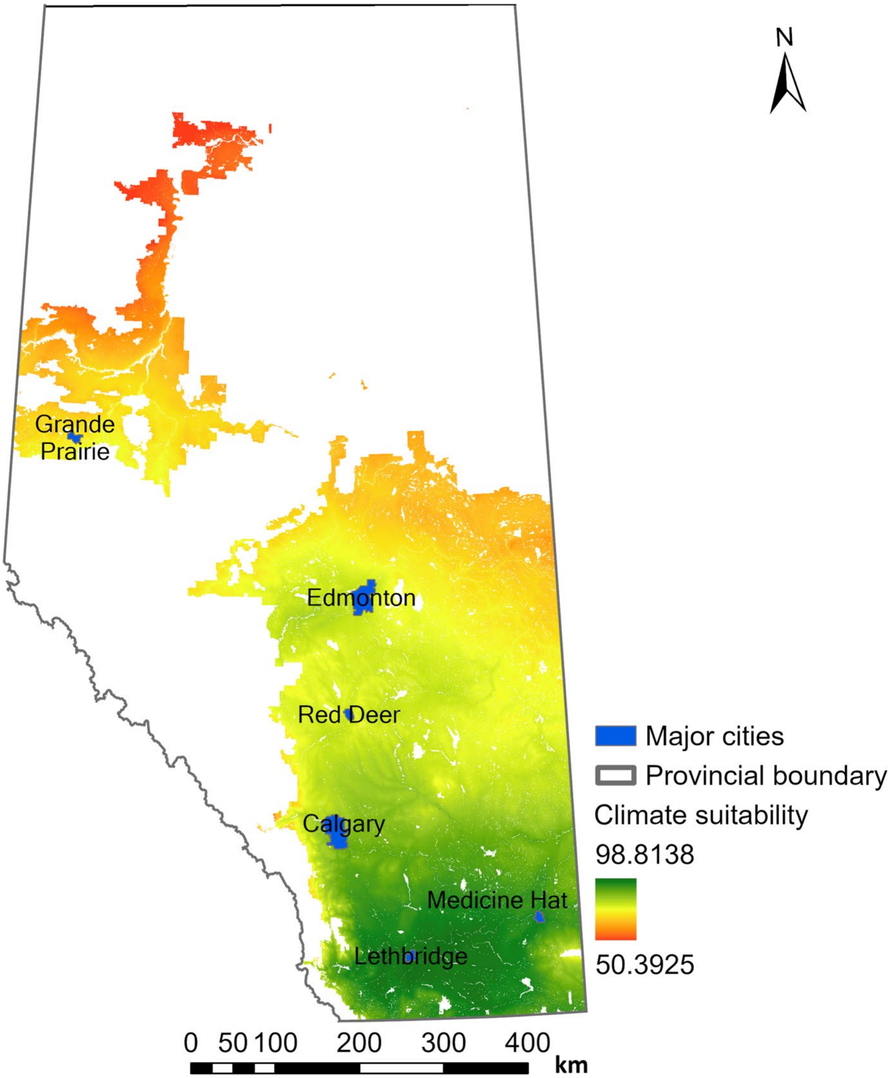

Fig. 5 Spatial distribution of climate suitability in Alberta based on HDD, GHI, and FFD. Higher values indicate more favourable operating-climate conditions for CEA development. White, blank, or no-data cells are not scored and should not be interpreted as climate suitability scores of zero

and terrain conditions. In contrast, large parts of northern Alberta and mountainous areas in western Alberta were either screened out or assigned lower priority because of overlapping policy-screening, terrain, and infrastructure limitations. Overall, the baseline surface was more strongly aligned with infrastructure-connected corridors than with environmentally favourable but relatively isolated locations.

The classified planning-priority surface further showed that most eligible land was assigned to the moderate class. Of the 968,306 classified eligible cells, 534,490 cells were classified as moderate, corresponding to 133,622.50 km^2 or 55.20% of the classified eligible area. High and Very High planning-priority areas were much more spatially selective, covering 37,238.75 km^2 and 2,328.50 km^2, respectively. Together, these two classes represented 16.35% of the classified eligible area and only 5.99% of the provincial analysis area.

Regional tabulation by LUF planning regions showed that High and Very High planning-priority land was strongly concentrated in central and southern Alberta. The South Saskatchewan region contained the largest High and Very High planning-priority area, with 15,705.00 km^2, followed by the North Saskatchewan region with 10,146.50 km^2 and the Red Deer region with 9,204.50 km^2. Together, these three regions accounted for 88.60% of all High and Very High planning-priority land identified in the classified eligible area. This concentration indicates that the baseline priority pattern is regionally uneven and strongly aligned with central and southern Alberta.

The small difference between the eligible cells reported in Table 4 and the classified cells reported in Tables 5 and 6 reflects 72 eligible cells, or 18.00 km^2, that were retained by the final mask but not assigned a classified planning-priority value because of NoData alignment in the integrated suitability layers.

Sensitivity and Robustness Analyses

The baseline configuration is presented first to establish the reference spatial pattern against which the subsequent sensitivity and robustness results are evaluated.

The top-level weighting sensitivity analysis showed that the baseline planning-priority pattern was robust at the provincial scale (see Table 7). Pixel-wise Pearson correlation coefficients between the baseline configuration (S4) $(0.75/0.25)$ and the alternative top-level weighting configurations ranged from 0.97931 to 0.99730, with corresponding R^2 values from 0.95905 to 0.99461. These values indicate strong agreement in the overall spatial pattern across configurations.

Greater variation was observed in the top 10% high-priority areas. Relative to the baseline configuration (S4), the overlap ratios were 51.95%, 67.60%, 83.11%, and 97.83% for the 0.55/0.45, 0.60/0.40, 0.667/0.333, and 0.85/0.15 configurations, respectively. This result indicates that the broad regional geography of CEA planning priorities remained stable, while the exact configuration of the highest-priority areas was more sensitive to the balance between infrastructure accessibility and environmental suitability.

A parallel accessibility-weight robustness analysis varied the internal accessibility weights while retaining the same hard-constraint structure, environmental module, and top-level baseline weights (see Table 8). Relative to the baseline configura-

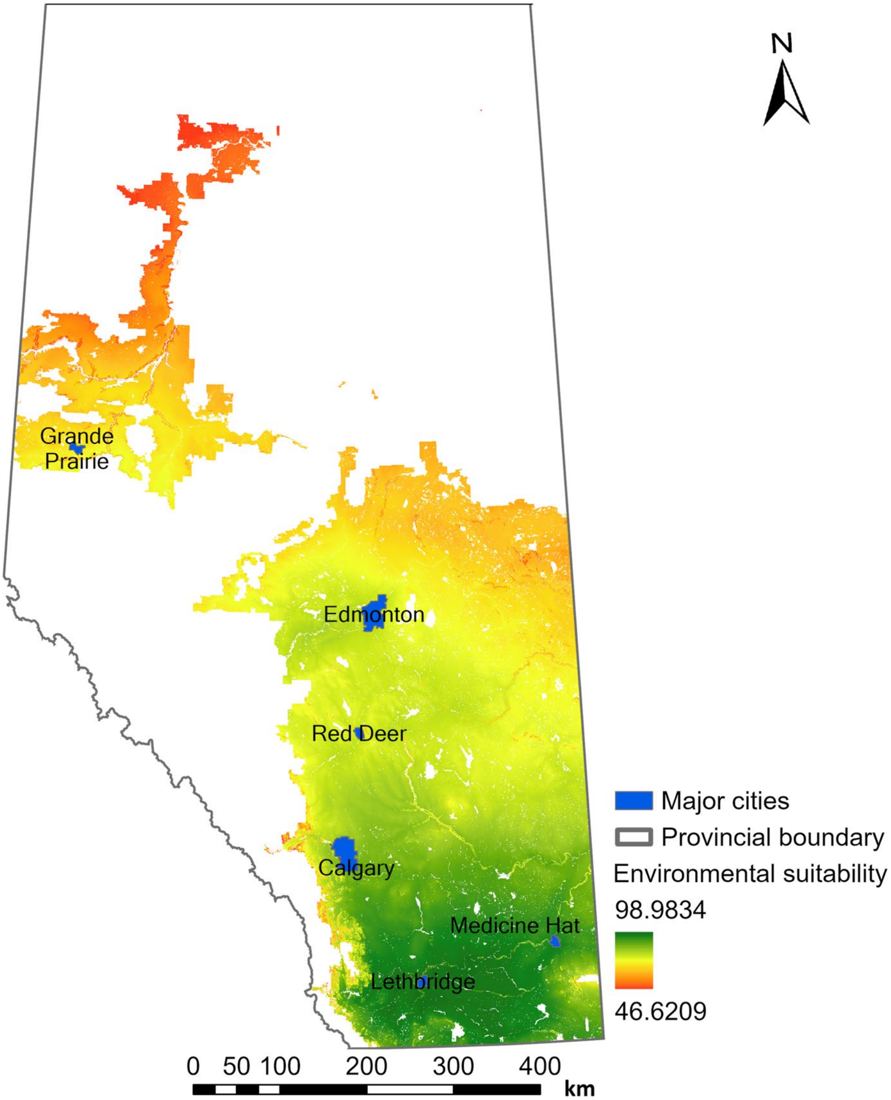

Fig. 6 Spatial distribution of environmental suitability after integrating operating-climate and slope conditions. White, blank, or no-data cells are not scored and should not be interpreted as environmental suitability scores of zero

tion, Pearson correlation coefficients were 0.99106, 0.95151, and 0.92107 for AR1, AR2, and AR3, respectively, with corresponding R^2 values of 0.98220, 0.90537, and 0.84837.

Top-decile overlap ratios were also substantial, ranging from 79.20% to 92.61%. These results indicate that the central and southern Alberta priority pattern was not dependent on a single AHP accessibility-weighting configuration, even when pipe-

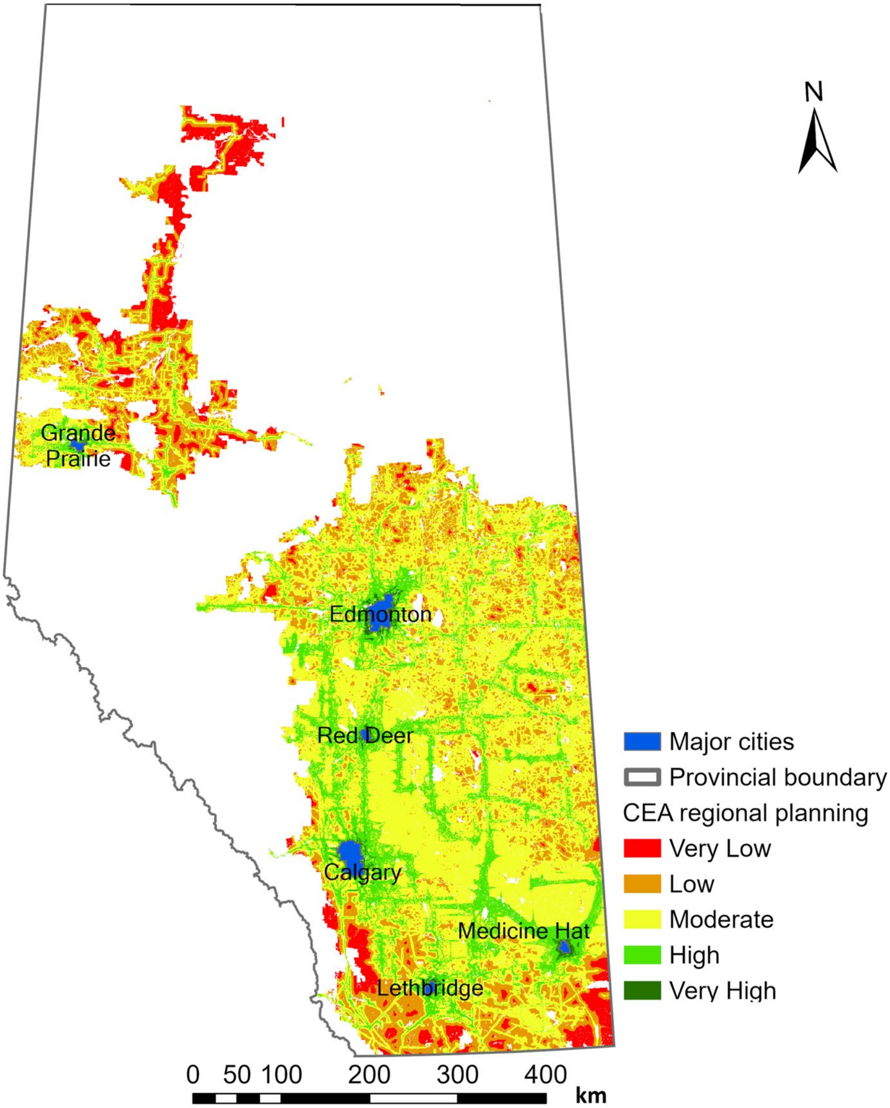

Fig. 7 Baseline CEA planning-priority surface for Alberta under the baseline infrastructure-priority configuration (0.75 accessibility / 0.25 environmental suitability). Areas excluded by the final hard-constraint mask are shown as no-data and should not be interpreted as planning-priority scores of zero

line weight was reduced and water, road, powerline, or city weights were increased (Table 9).

A policy-mask sensitivity analysis examined the influence of the conservative Green Area exclusion. When provincial Green Area lands were treated as conditional rather than excluded, the eligible land base increased from 242,094.50 km^2 to 524,970.75 km^2, corresponding to an increase from 36.64% to 79.45% of the provin-

Table 5 Cell counts, areas (km^2), and area percentages for CEA planning-priority classes

Planning-priority class	Cell count	Area (km^2)	Eligible area (%)	Provincial area (%)
Very low	68,734	17,183.50	7.10	2.60
Low	206,813	51,703.25	21.36	7.83
Moderate	534,490	133,622.50	55.20	20.22
High	148,955	37,238.75	15.38	5.64
Very high	9,314	2,328.50	0.96	0.35
Total	968,306	242,076.50	100.00	36.64

Table 6 Regional distribution of CEA planning-priority class areas (km^2) within the eligible land base and high/very high area share (%)

Planning region	Very low (km^2)	Low (km^2)	Moderate (km^2)	High (km^2)	Very high (km^2)	Eligible area (km^2)	High/Very high (%)
Lower Athabasca	194.00	2,059.25	4,420.75	613.25	0.00	7,287.25	8.42
Lower Peace	6,709.00	3,883.25	2,360.25	152.25	0.00	13,104.75	1.16
North Saskatchewan	226.50	10,038.50	36,880.25	9,208.25	938.25	57,291.75	17.71
Red Deer	269.00	5,675.75	32,935.00	9,006.00	198.50	48,084.25	19.14
South Saskatchewan	5,741.50	14,018.25	34,668.50	14,582.25	1,122.75	70,133.25	22.39
Upper Athabasca	1,594.25	7,393.50	11,579.75	1,595.75	0.00	22,163.25	7.20
Upper Peace	2,449.25	8,634.75	10,778.00	2,081.00	69.00	24,012.00	8.95
Total	**17,183.50**	**51,703.25**	**133,622.50**	**37,238.75**	**2,328.50**	**242,076.50**	**16.35**

Table 7 Top-level weighting sensitivity analysis comparing alternative weighting configurations with the S4 (Baseline) infrastructure-priority configuration (0.75 accessibility / 0.25 environmental suitability). Pearson's r and R^2 are dimensionless; top-decile overlap is reported as a percentage

Configuration	Pearson's r	R^2	Top 10% overlap (%)
0.55 / 0.45	0.97931	0.95905	51.95
0.60 / 0.40	0.98962	0.97935	67.60
0.667 / 0.333	0.99727	0.99455	83.11
0.85 / 0.15	0.99730	0.99461	97.83

cial analysis area. However, High and Very High planning-priority areas increased only from 39,567.25 km^2 to 42,853.50 km^2.

Under the alternative policy-mask configuration, 83.09% of High and Very High planning-priority land remained concentrated in the South Saskatchewan, North Saskatchewan, and Red Deer planning regions. This result shows that Green Area treatment strongly affects the estimated eligible land base, while the broad central and southern Alberta priority pattern remains relatively stable.

Figure 8 shows the policy-mask sensitivity result when provincial Green Area lands are allowed as possible, but conditional, locations for CEA development. This provides a simple check of how sensitive the priority rankings are to this policy choice, while still excluding federal lands, protected areas, major water bodies, and areas steeper than 8°.

Table 8 Robustness of the baseline planning-priority pattern across four internal accessibility-weighting structures: the baseline configuration and three alternatives (AR1–AR3). Weights, Pearson's r, and R^2 are dimensionless; top-decile overlap is reported as a percentage

Weight or robustness measure	Baseline	AR1	AR2	AR3
City weight	0.267	0.300	0.280	0.380
Road weight	0.107	0.100	0.150	0.140
Pipeline weight	0.427	0.350	0.250	0.200
Powerline weight	0.167	0.200	0.220	0.180
Water weight	0.033	0.050	0.100	0.100
Pearson's r	1.00000	0.99106	0.95151	0.92107
R^2	1.00000	0.98220	0.90537	0.84837
Top 10% overlap (%)	100.00	92.61	84.46	79.20

Table 9 Comparison between the baseline policy mask and the alternative policy-mask configuration

Indicator	Baseline mask	Alternative mask
Eligible area (km^2)	242,094.50	524,970.75
Eligible area (% of provincial analysis area)	36.64	79.45
High + Very High area (km^2)	39,567.25	42,853.50
High + Very High area (% of eligible/classified area)	16.35	8.17
High + Very High area (% of provincial analysis area)	5.99	6.49
Share of High + Very High area in South Saskatchewan, North Saskatchewan, and Red Deer (%)	88.60	83.09

A separate occupied-footprint sensitivity scenario removed clearly mapped road footprints, established urban, rural, and country residential footprints, and industrial occupation footprints from the baseline eligible area. This conservative mask removed 10,920 cells. At 500 m × 500 m resolution, this corresponds to 2,730.00 km^2, reducing the total eligible area from 242,094.50 km^2 to 239,364.50 km^2, or 1.13% of the baseline eligible area (Table 10). Of the removed cells, 7,241 were originally classified as High or Very High, corresponding to 1,810.25 km^2. High + Very High planning-priority area declined from 39,567.25 km^2 to 37,757.00 km^2, a 4.58% reduction. High and Very High cells accounted for 66.31% of all removed area, indicating that developed footprints were disproportionately concentrated in high-scoring areas. This pattern is consistent with the role of accessibility and proximity to population and infrastructure in the model, but 95.42% of baseline High + Very High land remained after the occupied-footprint mask was applied, indicating that the area-based provincial results were reasonably robust.

The classification-method sensitivity analysis showed that the total area assigned to the upper two classes was strongly affected by the classification rule. High and Very High planning-priority area increased from 39,567.25 km^2 under the baseline equal-interval classification to 96,984.25 km^2 under equal area and 109,922.75 km^2 under natural breaks (Table 11). The alternative methods classified larger areas as High or Very High because their upper-class thresholds were lower: the equal-area High and Very High score ranges were 58.966267–64.180183 and 64.180267–98.689133, respectively, and the natural-breaks High and Very High score ranges

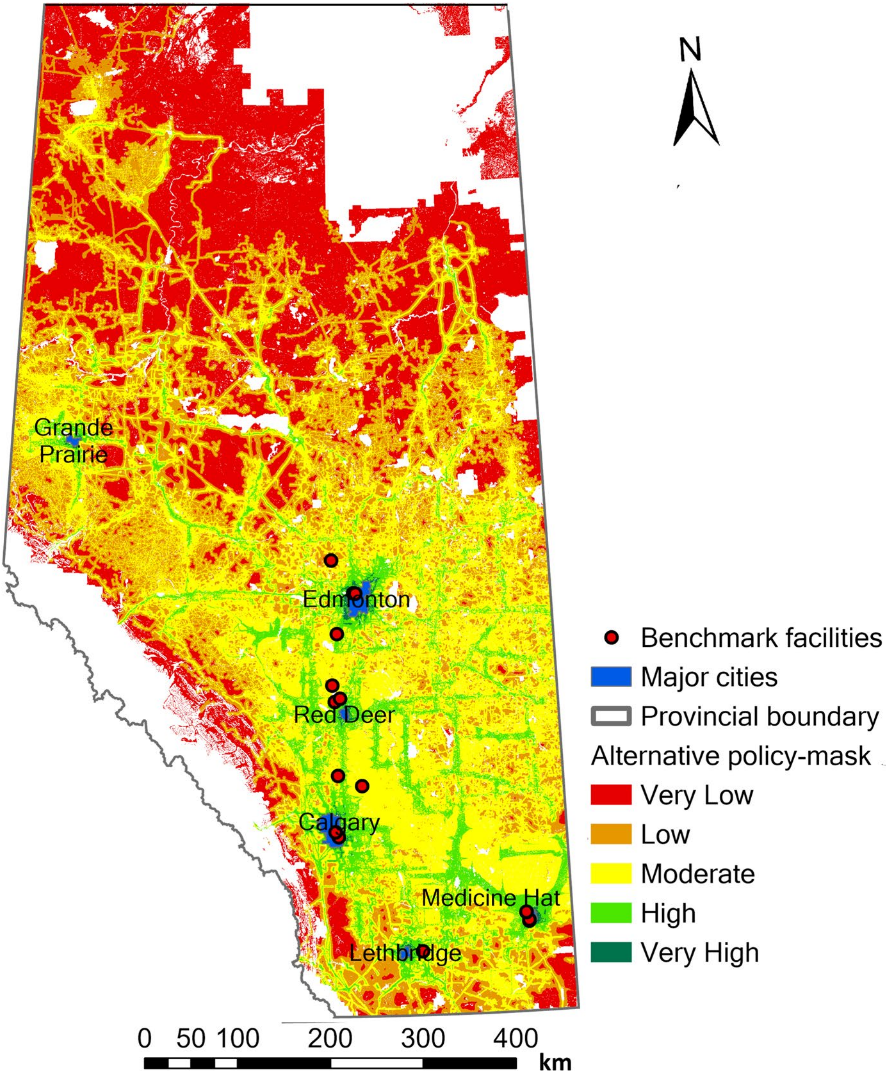

Fig. 8 Alternative policy-mask configuration. In this sensitivity analysis, provincial Green Area lands were treated as conditional rather than excluded, while federal lands, protected areas, major water bodies, and areas with slope values greater than 8° remained excluded. White, blank, or excluded cells indicate mask status rather than suitability scores

were 57.606987–67.487106 and 67.487198–98.689133, respectively. Nevertheless, both alternative methods retained 100.00% of the baseline High and Very High cells. The resulting Jaccard similarities of 40.80% for equal area and 36.00% for natural breaks therefore reflect expansion of the alternative upper-class sets rather than displacement of the baseline core.

South Saskatchewan remained the largest contributor to High and Very High planning-priority area under all three classification methods (Table 12). South Saskatch-

Table 10 Comparison of baseline results and the conservative occupied-footprint sensitivity scenario

Metric	Baseline	Occupied-footprint sensitivity	Change
Eligible area	242,094.50km^2	239,364.50 km^2	-2,730.00km^2 (-1.13%)
High + Very High planning-priority area	39,567.25 km^2	37,757.00 km^2	-1,810.25km^2 (-4.58%)

Table 11 Robustness of High and Very High planning-priority areas across three alternative five-class classification methods: baseline equal interval, equal area, and natural breaks

Area or robustness measure	Baseline equal interval	Equal area	Natural breaks
High + Very High area (km^2)	39,567.25	96,984.25	109,922.75
Share of classified eligible area (%)	16.35	40.06	45.41
Jaccard overlap with baseline (%)	Reference	40.80	36.00
Baseline High + Very High retention (%)	Reference	100.00	100.00
Core three-region share (%)	88.60	86.09	85.47

Table 12 Regional distribution of High and Very High planning-priority area under alternative classification methods

Planning region	Baseline equal interval (km^2)	Equal area (km^2)	Natural breaks (km^2)
Lower Athabasca	613.25	2,073.50	2,468.50
Lower Peace	152.25	678.25	874.00
North Saskatchewan	10,146.50	24,862.75	28,415.50
Red Deer	9,204.50	25,252.75	28,506.00
South Saskatchewan	15,705.00	33,382.25	37,032.25
Upper Athabasca	1,595.75	5,329.75	6,284.75
Upper Peace	2,150.00	5,405.00	6,341.75
Total	**39,567.25**	**96,984.25**	**109,922.75**

ewan, North Saskatchewan, and Red Deer jointly accounted for 88.60% of High and Very High planning-priority area under the baseline equal-interval classification, 86.09% under equal area, and 85.47% under natural breaks. Under the two alternative classifications, Red Deer slightly exceeded North Saskatchewan, but the same three central and southern regions remained dominant. These results indicate that class-based area totals are method-sensitive, while the baseline upper-priority core and broad central and southern Alberta concentration are robust.

Benchmark-Based Empirical Plausibility Assessment

Empirical plausibility refers here to the extent to which independently identified existing CEA facilities receive relatively high modelled planning-priority scores compared with a background sample of eligible locations. It does not constitute predictive validation, causal verification, or evidence that the current facilities represent optimal locations.

Planning-priority scores were extracted for 16 identifiable food-production-related CEA and greenhouse benchmark facilities in Alberta that were not used in model construction, weight specification, or parameter calibration (see Table 13). Scores were also extracted for 1000 random points generated within the eligible land base. The comparison was used as a benchmark-based empirical plausibility assessment of whether identifiable food-production-related facilities occupied higher-scoring locations than the broader pool of eligible land.

Under the baseline configuration (S4), extracted scores for the 16 benchmark facilities ranged from 49.39 to 88.19, with a mean of 71.69 and a median of 73.28. Eleven of the 16 benchmark facilities received baseline scores above 60, and eight received scores above 70. By contrast, the 1000 random eligible points had a mean score of 54.00 and a median of 56.62 under the baseline configuration (S4).

A clear pattern was observed across the alternative top-level weighting configurations. Most benchmark facilities received lower scores as the accessibility weight increased from S1 to S5. This decline was especially pronounced for Doef's Greenhouses Ltd., Shirley's Greenhouse, Inspired Greens (Coaldale), and Sunterra Greenhouse, indicating greater sensitivity to stronger infrastructure-oriented weighting. By contrast, groHERE Harvest showed a slight increase as accessibility weight increased, while Big Marble Farms, Sunshine Greenhouses Ltd., and Westland Fresh Produce remained highly ranked across all configurations.

The comparison with the unrestricted random eligible-point sample showed the same descriptive pattern across all five top-level weighting configurations (see Table 14). Benchmark facilities had consistently higher mean and median scores than random eligible points. Mean differences ranged from 14.47 to 19.30, nominal

Table 13 Extracted planning-priority scores (0–100 scale) for benchmark facilities under five top-level weighting configurations

Facility	S1	S2	S3	S4 (Baseline)	S5
	(0.55/0.45)	(0.60/0.40)	(0.667/0.333)	(0.75/0.25)	(0.85/0.15)
groHERE Harvest	86.27	86.55	86.94	87.42	87.99
GoodLeaf Farm	80.83	80.07	79.05	77.78	76.25
Sunterra Greenhouse	65.33	63.42	60.85	57.67	53.83
Big Marble Farms	90.16	89.66	89.01	88.19	87.21
Inspired Greens (Coaldale)	76.35	74.44	71.87	68.68	64.85
Doef's Greenhouses Ltd.	57.89	55.76	52.92	49.39	45.14
Gull Valley Greenhouses Ltd.	64.88	63.33	61.27	58.71	55.62
Deepwater Farms	82.17	81.59	80.81	79.84	78.68
Sunshine Greenhouses Ltd.	89.78	89.26	88.56	87.70	86.66
Shirley's Greenhouse	63.40	61.40	58.72	55.39	51.39
Westland Fresh Produce	89.14	88.62	87.92	87.06	86.02
Sunlight Growers	84.32	83.37	82.11	80.54	78.66
The S4 Veggie Store	72.80	72.04	71.02	69.76	68.24
Swiss Leaf Innovation Inc.	67.44	66.26	64.67	62.70	60.33
Vertical Roots Edmonton	78.49	78.07	77.50	76.80	75.96
Vertical Roots Leduc	65.53	64.00	61.95	59.41	56.35

Table 14 Descriptive comparison of planning-priority score statistics and effect-size measures between benchmark facilities and 1000 unrestricted random eligible points across five top-level weighting configurations: S1 (0.55/0.45), S2 (0.60/0.40), S3 (0.667/0.333), S4 (baseline; 0.75/0.25), and S5 (0.85/0.15)

Statistic or comparison measure	S1	S2	S3	S4 (Baseline)	S5
Benchmark mean score	75.92	74.87	73.45	71.69	69.57
Benchmark median score	77.42	76.26	74.69	73.28	72.10
Random mean score	61.45	59.59	57.09	54.00	50.27
Random median score	63.29	61.67	59.38	56.62	52.82
Mean difference (score)	14.47	15.27	16.35	17.69	19.30
Nominal Mann–Whitney p	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Cliff's δ	0.63	0.63	0.63	0.63	0.63

Mann–Whitney U tests showed score separation in every configuration ($p < 0.001$), and Cliff's delta values of approximately 0.63 indicated substantial non-parametric separation between the two score distributions. Because spatial dependence may violate strict independence assumptions among nearby background points, the Mann–Whitney p-values are retained as nominal descriptive results rather than treated as the primary inferential evidence. The principal evidence comes from the consistency of descriptive differences and effect-size patterns, including the spatial-thinning robustness check reported in Table 15.

The repeated spatial-thinning analysis produced the same directional result across all ten samples and all five weighting configurations. All ten thinned eligible-background samples contained 50 points, and benchmark facilities had higher mean and median scores than the thinned eligible-background samples in every repetition and every configuration.

All benchmark–background mean-difference ranges, median-difference ranges, and Cliff's delta ranges remained positive. Under S4 (Baseline), the thinned-background mean range was 48.31–53.50, the benchmark–background mean-difference

Table 15 Robustness of benchmark comparisons across ten spatially thinned eligible-background samples

Benchmark and comparison metric	S1	S2	S3	S4 (Baseline)	S5
Benchmark mean	75.92	74.87	73.45	71.69	69.57
Benchmark median	77.42	76.26	74.69	73.28	72.10
Thinned mean range	56.40–60.70	54.38–58.90	51.67–56.49	48.31–53.50	44.26–49.90
Thinned median range	59.29–62.32	57.43–60.63	54.20–59.05	50.07–57.05	45.71–53.98
Mean-difference range	15.23–19.52	15.97–20.48	16.96–21.78	18.19–23.38	19.67–25.31
Median-difference range	15.10–18.13	15.62–18.82	15.63–20.48	16.23–23.21	18.12–26.39
Cliff's δ range	0.655–0.770	0.652–0.772	0.657–0.762	0.642–0.762	0.632–0.762

range was 18.19–23.38, and Cliff's delta ranged from 0.642 to 0.762. This indicates that the benchmark–background separation did not depend on a single dense random-point realization. Because Moran's *I* remained positive at the selected separation distance, the analysis is interpreted as a robustness check under reduced local spatial redundancy rather than as evidence of fully independent spatial observations.

Because the benchmark facilities were independent of model construction and tended to score higher than both unrestricted and spatially thinned eligible-background locations, the comparison provides descriptive support for the plausibility of the spatial policy-screening framework.

Discussion

Spatial Selectivity and Provincial Land-use Priorities

Taken together, the results point to a small and regionally concentrated provincial screening space, an infrastructure-led but broadly robust spatial pattern, and a strong influence of the Green Area assumption on the estimated eligible land base. These findings suggest that CEA planning in Alberta is best treated as an early-stage land-use and infrastructure-coordination problem. The framework is therefore most useful for distinguishing constrained land from candidate areas requiring further review, rather than for direct implementation decisions.

The results show that CEA planning priorities in Alberta are highly spatially selective. After hard-constraint masking, only 36.64% of the provincial analysis area remained eligible for assessment, and High and Very High planning-priority classes together accounted for only 5.99% of the provincial analysis area. Alberta's large land base therefore does not translate into a broadly available provincial screening space for commercial CEA promotion. Instead, early-stage planning must begin from a constrained geography of eligible land, infrastructure access, environmental conditions, and terrain feasibility.

The regional distribution of High and Very High planning-priority land reinforces this interpretation. The South Saskatchewan, North Saskatchewan, and Red Deer planning regions together accounted for 88.60% of all High and Very High planning-priority land identified in the classified eligible area. This concentration indicates that central and southern Alberta dominate the provincial opportunity structure because eligible land, infrastructure networks, urban access, and agricultural development capacity are more closely aligned in these regions. In policy terms, CEA expansion is therefore better understood as a regional resource-allocation and infrastructure-coordination problem than as a generic land-availability question.

This result also differentiates CEA planning from conventional open-field agricultural suitability assessment. Field agriculture remains closely tied to soil quality, growing-season length, precipitation, and agro-climatic limits. CEA reduces some of these direct environmental constraints through technological control, but it does not remove geography from the decision. Instead, geography reappears through infrastructure access, operating costs, energy systems, service availability, logistics, water access, and proximity to demand (Gómez et al., 2019; Ahamed et al., 2019; Engler &

Krarti, 2021). In Alberta, environmentally favourable areas are therefore not necessarily the strongest candidates for commercial CEA if they are weakly connected to the infrastructure and settlement systems needed for year-round production.

Lower-priority areas in northern and western Alberta should therefore be interpreted as differentiated planning areas rather than as areas where CEA is impossible. These regions may still support smaller, locally adapted, publicly supported, or food-security-oriented CEA projects, particularly where community resilience or northern supply security is the main policy objective. However, the framework suggests that near-term commercial CEA expansion is more likely to be efficient in regions where eligible land, infrastructure access, and market proximity coincide. This interpretation is consistent with recent land-use policy research showing that spatial planning outcomes are shaped by the interaction between local suitability, accessibility, regional functions, food-security objectives, and differentiated policy priorities.

Infrastructure-led Priorities and Robustness

Infrastructure accessibility played a central role in shaping the baseline planning-priority pattern because it is closely tied to the operating requirements of CEA in a cold-region province. The highest-priority areas were not simply those with favourable environmental conditions. They were locations where environmental conditions coincided with pipeline proximity, urban access, road connectivity, powerline access, and water-resource proximity. This explains why the final planning-priority surface aligned more closely with infrastructure-connected corridors than with broad climatic gradients alone.

The top-level weighting sensitivity results support this interpretation. Across the alternative top-level weighting configurations, Pearson correlation coefficients between the baseline configuration (S4) and alternative planning-priority surfaces ranged from 0.97931 to 0.99730, with corresponding R^2 values from 0.95905 to 0.99461. The broad provincial pattern was therefore stable even when the balance between infrastructure accessibility and environmental conditions changed. However, top-decile overlap ratios varied more strongly, ranging from 51.95% under the 0.55/0.45 configuration to 97.83% under the 0.85/0.15 configuration. This indicates that the general regional pattern was robust, while the exact configuration of the highest-priority cells remained sensitive to the strength of the infrastructure-priority assumption.

Pipeline proximity was especially influential in the Alberta baseline configuration, but it should not be interpreted as a universal requirement for CEA development. Its role reflects Alberta's energy geography and the heating burden associated with greenhouse production in a cold climate (Ahamed et al., 2019; Iddio et al., 2020; GoA, 2020; Mirza, 2023). In this framework, pipeline proximity was used only as a screening-level proxy for energy-related infrastructure geography, not as evidence of direct connection feasibility, fuel availability, ownership access, or project-level energy cost. The accessibility-weight configurations with reduced pipeline weights likewise indicate that future CEA development may follow more diversified energy pathways, including electricity, waste heat, heat pumps, or other low-carbon heating systems.

The accessibility-weight robustness analysis further shows that the infrastructure pattern was not driven by a single AHP configuration. When the internal accessibility weights were varied, Pearson correlation coefficients remained high across AR1, AR2, and AR3, with values of 0.99106, 0.95151, and 0.92107, respectively. Top-decile overlap ratios also remained substantial, ranging from 79.20% to 92.61%. These results suggest that the central and southern Alberta pattern reflects the spatial co-location of multiple infrastructure systems rather than a narrow artefact of the baseline accessibility weights. They also partly address concern about the low baseline weight assigned to water proximity. Although water proximity received a baseline accessibility weight of 0.033, its weight increased to 0.050 in AR1 and to 0.100 in AR2 and AR3, while the broad regional pattern remained stable. Even so, the water variable should still be read as a screening-level accessibility proxy rather than as evidence that water access has been resolved.

For planning interpretation, robustness should not be judged only from province-wide correlation coefficients. High overall correlation can coexist with locally meaningful reclassification, especially near class boundaries or within the top-decile priority areas that are most likely to attract planning attention. The reported overlap ratios, regional shares of high and very high priority land, policy-mask sensitivity results, and benchmark-facility score changes therefore provide complementary evidence about spatial stability. In this study, the broad regional pattern remained stable under the weighting analyses, but the top 10% overlap values and regional shares show that the exact location and distribution of the highest-priority cells can still change under alternative assumptions. Such local changes may be meaningful for regional comparison, infrastructure sequencing, or municipal follow-up even when province-wide correlations remain high.

The classification-method sensitivity results distinguish the robustness of the underlying continuous spatial pattern from the sensitivity of categorical area totals. Equal-area and natural-breaks classifications assigned substantially larger areas to the upper classes because their class thresholds were lower than those of the baseline equal-interval classification. The full retention of baseline High and Very High cells under both alternatives indicates that the baseline captures a stable high-scoring core, while the alternative methods broaden the surrounding upper-priority zone. The baseline equal-interval classification is therefore best interpreted as a transparent and comparatively selective reporting convention, not as a uniquely correct zoning rule. Policy conclusions should rely primarily on the continuous baseline planning-priority surface, broad regional concentration, and sensitivity results rather than treating class thresholds as fixed regulatory boundaries.

The occupied-footprint sensitivity analysis further clarifies the relationship between modelled suitability and actual land availability. Some high-scoring cells overlapped mapped roads, established urban, rural, and country residential footprints, and industrial occupation, which is plausible because accessibility, urban proximity, and infrastructure access are positively weighted in the framework. Removing these occupied footprints reduced total eligible area by 2,730.00 km^2, or 1.13% of the baseline eligible land base, and reduced High + Very High planning-priority area by 1,810.25 km^2, or 4.58%. This modest area-based effect did not materially alter provincial-scale area totals, but the larger proportional effect within the High and Very High classes shows that developed-land overlap should not be ignored in follow-up planning.

These results reinforce the distinction between spatial suitability and immediate parcel availability. A high modelled planning-priority score indicates favourable proximity to the criteria represented in the provincial screening framework, not that a parcel is vacant, developable, correctly zoned, serviced, or available for acquisition. Regional screening should therefore be followed by parcel-level evaluation of ownership, zoning, servicing, development status, and site feasibility. At the same time, some developed or industrial sites may still support non-ground-based CEA systems, including vertical farms, plant factories, adaptive reuse, warehouse conversion, or building-integrated production. The occupied-footprint sensitivity scenario should therefore be interpreted as a robustness test of mapped existing occupation, not as evidence that every developed or industrial footprint is permanently unsuitable.

Policy Implications

From a land-use policy perspective, the main contribution of the framework is that it separates land screened out under adopted policy or physical constraints from retained eligible land that varies in relative planning priority (Malczewski, 2006; Akıncı et al., 2013). This distinction matters for cold-region CEA because protected lands, major water bodies, steep terrain, infrastructure access, heating demand, water access, and market proximity do not operate in the same way in early-stage planning. The dual treatment of slope also improves interpretability by excluding steep terrain while still distinguishing relatively flat land from more marginal land within the retained eligible area.

The Green Area policy-mask sensitivity analysis further clarifies the policy meaning of the results. When provincial Green Area lands were treated as conditional rather than excluded, the eligible land base increased from 36.64% to 79.45% of the provincial analysis area. By contrast, High and Very High planning-priority land increased only from 5.99% to 6.49% of the provincial analysis area. The regional pattern also remained highly concentrated in South Saskatchewan, North Saskatchewan, and Red Deer, which still contained 83.09% of all High and Very High planning-priority land under the alternative mask, compared with 88.60% under the baseline mask. This indicates that Green Area treatment strongly affects the estimated screening space, but it does not fundamentally alter the broad central and southern Alberta planning geography.

These findings imply that provincial CEA planning should not be framed as a generic land-availability exercise. It is more productively understood as a coordination problem linking land-use zoning, infrastructure investment, energy planning, water access, municipal servicing, transportation systems, and regional food-security objectives. In this sense, the framework contributes less by isolating single locations than by clarifying where provincial attention is more or less likely to be warranted under explicit screening assumptions.

Planning Interpretation, Distribution Trade-offs, and Workflow

The planning interpretation of the results depends on distinguishing spatial suitability, planning desirability, and site-specific feasibility. Spatial suitability in this study refers to the modelled pattern produced by the criteria, weights, masks, and assumptions represented in the GIS-MCDA framework. Planning desirability is broader: it depends on policy objectives such as regional equity, food security, resilience, infrastructure investment priorities, and local development goals. Site-specific feasibility is narrower and more detailed: it requires parcel-level information on zoning, land ownership, servicing capacity, water access, energy supply, construction and operating costs, approvals, and stakeholder review. A high modelled planning-priority score therefore does not automatically mean that an area should be developed, and a lower-scoring northern or remote area may still have strategic policy value if the planning objective emphasizes regional resilience, remote-community food security, or equity-oriented investment.

The current framework does not prescribe a target number of facilities, a target number of cells, equal geographic distribution, or the number of facilities that should be located in northern versus southern Alberta. It identifies relative spatial priorities under an infrastructure-oriented baseline and related sensitivity or robustness assumptions. Decision-makers would need to specify whether the desired provincial outcome is to concentrate CEA development in highly accessible and infrastructure-efficient areas, to encourage a more distributed geography of production, or to balance efficiency with regional resilience, remote-community food security, and equity-oriented investment. These are alternative planning objectives, not conclusions generated automatically by the current model.

A practical planning workflow would use the model as an early-stage screen rather than as a final site-selection procedure. First, the provincial map can identify broad candidate areas and constrained regions. Second, regional comparisons can be made against infrastructure, food-system, and development objectives. Third, municipalities can review land use, zoning, servicing, and local development constraints. Fourth, candidate parcels can undergo technical and financial feasibility assessment, including water, energy, cost, and connection review. Fifth, stakeholders and communities can evaluate local priorities, trade-offs, and acceptability. Finally, investment or approval decisions can be made using project-specific evidence. The framework supports the first stages of this workflow, but it does not replace municipal review, parcel-level feasibility analysis, stakeholder engagement, or final investment and approval decisions.

Benchmark Comparison and Empirical Plausibility

The benchmark comparison provides descriptive support for the spatial policy-screening framework. The 16 benchmark facilities were not used in model construction, weight specification, or parameter calibration, yet they generally occupied higher-scoring locations than the broader eligible land base. Under the baseline configuration (S4), the benchmark facilities had a mean score of 71.69 and a median of 73.28, compared with 54.00 and 56.62, respectively, for the 1000 unrestricted random eligible points. Across all five top-level weighting configurations, mean differences ranged from 14.47 to 19.30, nominal Mann–Whitney U results were consistent with score separation in every configuration ($p < 0.001$), and Cliff's delta values of approximately 0.63 indicated substantial non-parametric separation.

The spatial-thinning robustness analysis provides a more cautious check on this pattern than relying primarily on nominal significance from a dense spatial background sample. Across ten separately generated samples of 50 eligible-background points separated by at least 66 km, benchmark-background mean differences, median differences, and Cliff's delta values remained positive for every weighting configuration. This stability strengthens the empirical plausibility interpretation, but it does not constitute formal predictive validation or establish the benchmark facilities as ground truth. Existing facility locations remain influenced by firm-level strategies, historical land availability, ownership conditions, zoning, servicing, permitting, and local infrastructure arrangements that are not fully represented in the provincial screening framework.

This pattern suggests that the framework captures part of the locational logic of food-production-related greenhouse and indoor-farming development in Alberta. Several benchmark facilities, including Big Marble Farms, Sunshine Greenhouses Ltd., Westland Fresh Produce, groHERE Harvest, Deepwater Farms, and GoodLeaf Farm, received relatively high baseline scores. These examples indicate that many identifiable food-production-related operations are located where infrastructure access, environmental conditions, and urban or regional support factors overlap.

The benchmark comparison should nevertheless be interpreted cautiously. The benchmark dataset is not a complete inventory of Alberta's greenhouse or CEA sector, and existing facility locations may also reflect firm-specific strategies, historical land availability, ownership conditions, local permitting, and site-level infrastructure arrangements that are not fully represented in a 500 m provincial-scale framework. The comparison therefore supports empirical plausibility, but it should not be interpreted as a formal predictive test.

Transferability and Limitations

The framework may be transferable to other cold-region contexts, but its policy masks, factor weights, and infrastructure assumptions should be recalibrated for local conditions. Jilin Province in northeastern China provides an illustrative example. Like Alberta, Jilin has cold winters and strong seasonal constraints on open-field production (PGJP, 2024). However, the dominant facility-agriculture logic differs. Alberta's CEA planning is strongly shaped by energy- and infrastructure-intensive production, whereas Jilin's policy and technical context places greater emphasis on peri-urban vegetable supply, greenhouse park development, energy-saving greenhouse systems, and solar-greenhouse production (PGJP, 2021; Department of ARJP, 2021; The General Office of the PGJP, 2009; He et al., 2025a, b). The general screening logic could therefore be adapted to Jilin or other cold-region settings, but local greenhouse typologies, energy systems, market organization, and policy priorities would need to be recalibrated rather than transferred mechanically.

Several limitations should also be noted. City accessibility was represented through a simplified two-tier urban system and distance-decay functions rather than through labour-market structure, commuting patterns, service density, or demographic change (GoA, 2018, 2023). The framework also does not include land price, construction cost, energy connection cost, local policy incentives, electricity and gas tariff variation, or detailed permitting complexity (Ahamed et al., 2019; GoA, 2020).

Euclidean distance and the adopted decay parameters are appropriate for provincial screening, but they cannot substitute for network-based logistics analysis or project-level infrastructure connection assessment.

The environmental indicators represent current or historical climate conditions rather than future climate projections. Similarly, the accessibility and demand-related variables do not incorporate future population redistribution or population-growth scenarios. Long-term CEA infrastructure planning would benefit from future climate projections and demographic scenarios, but credible implementation would require explicit choices about climate models, emissions pathways, downscaling procedures, demographic projections, spatial allocation of population growth, and uncertainty treatment. These extensions are outside the scope of the current study and should be treated as future research rather than as results of the present framework.

Water proximity should not be interpreted as legal or physical water availability, because licensed withdrawal capacity, water quality, allocation status, seasonal reliability, basin-level constraints, and municipal servicing conditions require separate review. Likewise, the framework does not explicitly model Alberta's water-licensing, allocation-transfer, basin-management, municipal-servicing, or utility-connection regimes. It also does not represent electricity or gas connection procedures, transmission and distribution tariff structures, or approval requirements for new or upgraded utility infrastructure. The high-priority areas identified in this study should therefore be treated as candidate areas for further water-access, energy-supply, utility-connection, and regulatory review rather than as areas where these implementation conditions have already been satisfied (Asare et al., 2024).

The AHP weights used in this study represent a literature-informed, author-defined baseline configuration rather than a systematic elicitation of stakeholder preferences from government agencies, industry actors, utility providers, municipal planners, or regional development organizations (Cabrera-Barona et al., 2018). They should therefore be interpreted as explicit policy parameterization for provincial screening, not as empirical estimates of actual facility-location behaviour. The treatment of provincial Green Area lands also remains a policy-screening assumption rather than a competing legal interpretation (Koomen et al., 2011). The alternative mask is analytically useful because it shows how strongly the estimated eligible land base depends on this assumption, but it does not imply that Green Area lands should automatically enter the same near-term commercial planning space as baseline eligible land. Future research could use interviews, Delphi methods, or participatory MCDA to calibrate factor weights more directly across stakeholder groups and policy objectives.

The five planning-priority classes are post-processing categories applied to a continuous score surface. Class-specific area totals depend on the classification method: equal-area and natural-breaks classifications produced substantially larger High and Very High planning-priority areas than the baseline equal-interval classification. These categories should therefore not be interpreted as regulatory thresholds or naturally discrete suitability states. Future applications may report continuous scores, compare multiple classification methods, define policy thresholds through stakeholder input, or calibrate thresholds to explicit planning objectives.

The spatial-thinning robustness analysis reduced local spatial redundancy in the benchmark comparison, but it did not eliminate broad-scale spatial autocorrelation.

The 66 km separation distance corresponded to the first local z-score peak in the incremental spatial autocorrelation analysis of the baseline continuous planning-priority surface, not to an independence threshold. The benchmark analysis should therefore be interpreted as descriptive and robustness-oriented. Future work could use larger benchmark inventories, explicit spatial regression, spatial permutation, block resampling, or other spatially structured validation approaches where data availability permits.

Finally, the provincial scale and 500 m spatial resolution are appropriate for identifying broad development corridors and constrained regions, but they cannot replace municipal or parcel-scale feasibility studies (Malczewski, 2006; Yalew et al., 2016). The Human Footprint Inventory is suitable for landscape-level screening of mapped occupation, but it does not replace current cadastral, zoning, ownership, redevelopment, or parcel-level data. Future work could incorporate socio-economic and governance variables, refine the representation of urban support and water access, distinguish food-production CEA from other greenhouse subsectors more systematically, expand the benchmark dataset where additional facility information becomes available, and apply finer-scale analysis within the priority regions identified in this study.

Conclusion

This study shows that CEA planning in cold regions is not simply a matter of local site conditions or climate, but a broader spatial issue shaped by how land, infrastructure, and environmental factors come together across a region. By combining explicit land exclusions with a structured assessment of accessibility and environmental conditions, the framework shows that modelled planning-priority areas in Alberta are not evenly distributed. They are concentrated mainly in well-connected central and southern parts of the province, while northern and more remote areas remain more constrained under the adopted infrastructure-oriented screening assumptions.

The results also indicate that the broad spatial pattern remains stable under the weighting configurations tested, and the central and southern Alberta concentration remains stable under alternative classification methods, although local differences, class-based area totals, and top-priority overlap changes still matter for planning interpretation. This supports the use of the framework as a provincial screening tool, not as a final site-selection model or a development-allocation rule.

More broadly, the study demonstrates that CEA can be approached as a regional planning question in which spatial evidence helps identify candidate areas, constraints, and follow-up priorities. The framework does not prescribe how many facilities should be developed, where final investments should occur, or whether high-scoring areas should automatically be prioritized over lower-scoring areas with strategic policy value. Instead, it provides a starting point for regional comparison, infrastructure review, municipal planning, parcel-level feasibility assessment, and stakeholder discussion. Future work can build on this by incorporating economic and social considerations, future climate and population scenarios, and finer-scale analysis within candidate regions.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

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