

Mapping the evidence to support micronutrient management practices and recommendations in Ontario corn and soybean production

A SYSTEMATIC MAP

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Abstract

Background

Corn and soybean growers in Ontario face emerging challenges in micronutrient management, with crop performance and soil health increasingly dependent on nutrient availability. High-yielding cultivars place greater demands on soils, while intensive fertilizer use can lead to micronutrient imbalances that reduce yields. Ontario's variable soils and growing conditions further complicate management decisions, while inconsistent yield responses make it difficult for growers to confidently adopt best practices. Current provincial guidelines are outdated, and the research on micronutrients in corn and soybean production is difficult for stakeholders to access and navigate effectively. This systematic map addresses the review question: what scientific evidence exists to support micronutrient management practices and recommendations for corn and soybean production in Ontario? The map focuses on nine micronutrients (boron, chlorine, cobalt, copper, iron, manganese, molybdenum, nickel and zinc), with the goal of organizing the available literature, identifying gaps for future research, and making the mapped information more accessible to growers, agronomists, policymakers and industry partners.

Methods

This systematic map followed the Collaboration for Environmental Evidence (CEE) guidelines and the Reporting Standards for Systematic Evidence Syntheses (ROSES) with the review question structured using a Population, Concept and Context (PCC) framework. Peer-reviewed literature was searched in Web of Science, AGRICOLA (EBSCOhost) and the CABI Digital Library, supplemented by grey literature searches of Google Scholar and relevant organizational websites. Records were screened in Covidence through two sequential rounds of title/abstract screening followed by full-text screening. Eligible documents included peer-reviewed articles, extension reports, conference abstracts and industry publications published in English from 2010 onward. Included records were characterized using a structured extraction workbook, supported by an AI extraction assistant (ChatGPT, 5.4 thinking mode). Each record was assigned a four-level geographic tier, and a corresponding Ontario-relevance rating of high, moderate, low or none, based on continental glaciation history, temperate-climate similarity, and corn/soybean cropping-system similarity to Ontario. Records rated Tier 1 (high) or Tier 2 (moderate) Ontario relevance were prioritized for a second, deeper extraction stage capturing tissue sufficiency/range intervals, soil characteristics, fertilizer form/source, and additional management detail.

Review findings

The search and screening process identified 1,365 eligible records spanning publication years 2010–2025. Zinc (867 records), iron (515), manganese (387), boron (365) and copper (320) were the most represented micronutrients, while molybdenum, nickel, cobalt and chlorine were comparatively underrepresented. Field experiments (639) were the most common research approach, followed by greenhouse (368) and laboratory (209) research.

Soil application (468) and foliar application (365) were the leading intervention methods, and nutrient uptake (912), yield (756) and biomass (677) were the most frequently reported outcomes. Only 9.2% of the full dataset (126 of 1,365 records) was classified as high or moderate relevance to Ontario's glaciated, temperate corn and soybean production systems. Within this Ontario-relevant subset, zinc (80), iron (68) and manganese (65) again dominated, while nickel (3) and cobalt (2) were very sparsely represented. The Ontario-relevant subset was concentrated in field experiments (61) and guidance/extension documents (29), reported nutrient uptake (82), yield (71), soil properties (65) and diagnostic outcomes (45) most often, and was geographically concentrated in the United States (71), Poland (25), Germany (17) and Canada (5). Economic analyses were consistently underrepresented: only 94 of 1,365 records (6.9%) in the full dataset included an economic component, and this proportion dropped further within the Ontario-relevant subset, to 6 of 126 records (4.8%).

Conclusions

The international literature was much larger than the subset identified as potentially relevant to Ontario, and Ontario-relevant knowledge varied substantially among micronutrients and management questions. The map identifies specific diagnostic, contextual and economic information gaps, but does not establish which practices or tissue thresholds should be adopted. Research and guideline assessment should therefore address defined Ontario decision needs.

Keywords: *Micronutrients, Boron, Zinc, Iron, Manganese, Copper, Molybdenum, Nickel, Cobalt, Chlorine, Corn, Maize, Soybean*

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Background

Ontario's corn and soybean growers face emerging challenges related to micronutrient management, with yield potential and soil health increasingly dependent on the availability of essential micronutrients. Newer high-yielding cultivars and varieties have higher nutrient demands, which can deplete soil micronutrient levels faster than traditional varieties (Tarar et al 2022). Additionally, intensive use of macronutrient fertilizers can disrupt the balance of micronutrients, leading to deficiencies that reduce crop performance (Mallarino et al 2015). This challenge is further complicated by Ontario's diverse soil conditions and climate, which affect the availability and uptake of micronutrients. Inconsistencies in yield responses make it difficult for growers to confidently apply micronutrient best practices.

Ontario's current guidelines and recommendations for micronutrient management need to be updated. Accessing, navigating and interpreting the research on micronutrients is beyond the capacity and resources of growers and other stakeholders.

The project *Scientific Evidence to Support Micronutrient Management Practices and Recommendations for Corn and Soybeans in Ontario* was undertaken to make the evidence base for micronutrient management in Ontario corn and soybean production more accessible and useful. The project was designed to provide accessible, synthesized knowledge that can support management practices, inform the development and updating of recommendations and guidelines, and identify priorities for future research and innovation.

Three complementary reports address different elements of the project. This systematic map identifies and characterizes the available literature on nine micronutrients (boron, chlorine/chloride, cobalt, copper, iron, manganese, molybdenum, nickel and zinc) in corn and soybean production. It examines how the knowledge is distributed across micronutrients, crops, geographic regions, research approaches, management interventions and outcomes, and identifies the subset of records generated under conditions considered sufficiently comparable to Ontario for deeper analysis.

The systematic map provides the evidence foundation for the broader project. It establishes what literature is available, where knowledge is concentrated or limited, and how much of the international literature has greater potential relevance to Ontario production conditions. For the Ontario-relevant subset, deeper extraction provides additional information on soil characteristics, application practices, diagnostic thresholds, yield responses and economic analysis. The map does not determine which micronutrient practices should be adopted or establish new recommendations; rather, it provides an organized evidence base from which those questions can be examined. This distinction is consistent with the report's subsequent two-level analysis of the full 1,365-record dataset and the 126-record Ontario-relevant subset.

Using evidence to support micronutrient management practices and recommendations in Ontario corn and soybean production: a knowledge synthesis, interprets and integrates the

Ontario-relevant knowledge identified through the systematic map, organizing it into an applied decision pathway and examining how different forms of knowledge contribute to micronutrient management decisions. *Strengthening the evidence for micronutrient management practices and recommendations in Ontario corn and soybean production: a Research and Innovation Roadmap* draws on the findings of the systematic map and knowledge synthesis to identify opportunities to strengthen the evidence available for future micronutrient management, recommendations and decision-making.

The project also developed the [Ontario Corn and Soybean Micronutrients Knowledge Hub](#), a searchable knowledge base built from the systematic map results. The Knowledge Hub makes the mapped literature more accessible to farmers, agronomists, policymakers, researchers and other stakeholders, while the three reports provide progressively different ways of using that knowledge: mapping the available evidence, interpreting the Ontario-relevant knowledge, and identifying priorities for strengthening the evidence base.

Generative artificial intelligence use

Generative artificial intelligence was used in data extraction and classification as described in the Methods and was also used to support preparation of this report. Report-production uses included development and refinement of analytical visualizations, report organization and drafting, terminology and plain-language refinement, editorial revision, and structured quality-assurance reviews for evidence integrity, consistency, coherence, quantitative and reference consistency, and copy quality. AI-assisted outputs were subject to researcher review and revision throughout report development. Generative AI was not used as an independent source of scientific evidence, and responsibility for the analysis, interpretation, conclusions and final report rests with the authors.

Stakeholder engagement

The review question was formulated based on priorities identified by the project funders, the Grain Farmers of Ontario (GFO) and the Ontario Ministry of Agriculture, Food and Agribusiness (OMAFRA), as well as feedback from the Ontario Soil Management Committee (OSMC) during the proposal phase. Letters of support endorsing the project were also provided by OSMC and Fertilizer Canada during this phase.

Stakeholders guided the project through a Project Advisory Committee (PAC) including farmers, Certified Crop Advisors/agronomists, OMAFRA crop/soil specialists, scientists/researchers, and fertilizer-industry partners. Throughout the project, the PAC provided feedback on the protocol and on the design and functionality of the Knowledge Hub.

Objective of the review

- Develop an accessible knowledge base for micronutrient management in corn and soybean production.

- Provide accessible information that can support the assessment of micronutrient management practices for Ontario.
- Provide an organized account of the available literature to inform future assessment of policy and guideline updates.
- Identify priority areas for future research and innovation.

The primary review question: *What scientific evidence exists to support micronutrient management practices and recommendations for corn and soybean production in Ontario?*

The research question is based on the Population, Concept, Context (PCC) framework (Pollock et al. 2023):

Population: Corn and soybean cropping systems.

Concept: Micronutrients (boron, chlorine/chloride, cobalt, copper, iron, manganese, molybdenum, nickel, zinc)

Context: Any aspect of micronutrients related to corn and soybean production that can contribute to updated best practices or production recommendations, including but not limited to role/function, deficiency symptoms, diagnostic tests, management practices (including soil and foliar applications), critical/sufficient levels (plant tissue, soil), crop yield, nutrient use efficiency, soil fertility, plant health, and sustainability of production systems.

Methods

The design of the systematic map was informed by James et al. (2016), the Collaboration for Environmental Evidence (CEE) Guidelines and Standards for Evidence Synthesis in Environmental Management (CEE 2024), and the Reporting Standards for Systematic Evidence Syntheses (ROSES) (Haddaway et al. 2018); the review question follows the PCC framework of Pollock et al. (2023).

A protocol for the systematic map was registered on [PROCEED](#) and [CABI protocolRxiv](#).

Deviations from the protocol

- Data extraction and characterization were supported by a large language model assistant (ChatGPT, 5.4 thinking mode) operated under a structured extraction workbook.
- Title and abstract screening were conducted in two phases to reduce the volume of literature to a manageable size. Phase 1a included records published from 2005 onward; Phase 1b limited eligibility to records published from 2010 onward.
- Ontario relevance was determined using a four-level geographic tier classification (Tier 1–Tier 4), with a corresponding relevance rating of high, moderate, low or none, based on continental glaciation history, temperate-climate similarity, and similarity of

the corn and soybean cropping system to Ontario conditions. All eligible records were first characterized, and a second, more detailed data extraction (deep extraction) was conducted exclusively for records rated geographic Tier 1 or 2 (high or moderate Ontario relevance). This two-stage approach provided more detailed information for records with greater potential to inform Ontario interpretation and management.

Search terms and strings

Search terms related to each element (population, concept) were combined with the Boolean operator OR. Each element search string was searched separately, and the results from each search were combined using the Boolean operator AND. The following bibliographic databases/platforms were searched: Web of Science, CABI Digital Library, and AGRICOLA. The databases were accessed through institutional subscriptions at the University of Guelph and Brock University. The search strings used in each bibliographic database/platform are shown in Table 1.

Grey literature was identified through two supplementary routes: a search of Google Scholar, and targeted searches of the websites of relevant agricultural extension, government and industry organizations, including provincial and federal agriculture departments, national and provincial grains and oilseeds commodity organizations, fertilizer industry associations, the FAO, CGIAR, USDA-ARS, all 50 U.S. state extension services, and fertilizer manufacturers. Supplement Table S2 provides a complete list of the organizations and their URLs included in the grey literature searches.

Table 1. Search strings used in bibliographic databases.

Bibliographic Database/ Platform	Search String
Web of Science	((TS=(corn OR maize OR "Zea mays" OR "Z. mays")) AND TS=(micronutrient* OR boron OR chlorine OR cobalt OR copper OR iron OR manganese OR molybdenum OR nickel OR zinc)) OR ((TS=(soybean* OR "soy bean" OR soyabean* OR "Glycine max" OR "G. max")) AND TS=(micronutrient* OR boron OR chlorine OR cobalt OR copper OR iron OR manganese OR molybdenum OR nickel OR zinc))
CABI Digital Library	ab:(corn OR maize OR "Zea mays" OR "Z. mays" OR soybean* OR "soy bean" OR soyabean* OR "Glycine max" OR "G. max") AND ab:(micronutrient* OR boron OR chlorine OR cobalt OR copper OR iron OR manganese OR molybdenum OR nickel OR zinc) OR title:(...) AND title:(...)
Agricola (EBSCOhost)	AB(corn OR maize OR "Zea mays" OR "Z. mays" OR soybean* OR "soy bean" OR soyabean* OR "Glycine max" OR "G. max") AND AB(micronutrient* OR boron OR chlorine OR cobalt OR copper OR iron OR manganese OR molybdenum OR nickel OR zinc) OR TI(...) AND TI(...)

Search comprehensiveness

Search sensitivity was assessed against a pre-defined benchmark set of 20 articles known to be relevant to the review question. The combined search strings retrieved 18 of these 20 benchmark articles (90%), indicating that the search strategy was sufficiently sensitive to proceed to full screening.

Article screening and record eligibility criteria

Records were screened for eligibility in Covidence using a three-stage process: two rounds of title and abstract screening, followed by full-text screening. Two title and abstract screening phases were used to progressively narrow the search results and create a more focused, manageable dataset for full-text assessment. The first phase screened the broader body of records published from 2005 onward, while the second applied the more concentrated publication-period and topic criteria that supported the final review scope. Eligible documents included peer-reviewed journal articles, extension reports, conference abstracts and industry publications, provided that they were available in English and addressed corn and/or soybean cropping systems and at least one of the nine micronutrients of interest. The eligibility criteria, structured using the PCC elements of the review question, are summarized in Tables 2–5.

Table 2. Inclusion/exclusion criteria for both screening phases.

Inclusion Criteria	
Corn and soybean production systems; written in English; considers any of boron, chlorine, cobalt, copper, iron, manganese, molybdenum, zinc, nickel; addresses any aspect of micronutrient management; all study types (field, controlled environment, experimental, observational, review); peer-reviewed journal articles, book chapters, pre-prints, grey literature (unpublished reports, extension/advisory production recommendations, factsheets, industry trade publications), conference proceedings/abstracts.	

Table 3. Phase 1a – title and abstract screening inclusion/exclusion criteria.

Element	Include	Exclude
Population	Corn or soybean production systems	Crops other than corn or soybean
Concept /Context	Any of the following micronutrients in corn or soybean production: Boron, chlorine, cobalt, copper, iron, manganese, molybdenum, nickel, zinc in corn or soybean production	–
Record characteristics	Written in English; published from 2005	–

Table 4. Phase 1b – title and abstract screening inclusion/exclusion.

Element	Include	Exclude
Population	–	Subsistence farming systems
Concept/Context	–	Micronutrients as contaminants; micronutrients related to human nutrition
Record characteristics	Published from 2010	Data sets

Table 5. Full-text screening inclusion/exclusion criteria.

Element	Include	Exclude
Record characteristics	Published from 2010	Published before 2010 poor quality writing, study design or analysis

Data coding strategy

This phase of the systematic map process is often referred to as characterization or data extraction (Collaboration for Environmental Evidence, 2022). Eligible records underwent two stages of extraction: characterization of all included records, followed by deeper extraction of the Ontario-relevant subset. ChatGPT (5.4 thinking mode) was used as an extraction and classification assistant in both stages. Extraction was conducted using a structured workbook with predetermined variables, codes and controlled vocabularies. ChatGPT also assisted with assignment of geographic tier and Ontario-relevance classifications using the predefined criteria described in Table 7.

The AI-assisted extraction and classification process was iterative. Outputs were spot-checked against the source records to assess extraction accuracy and application of the predefined criteria. Where errors, inconsistencies or ambiguities were identified, the extraction and classification rules were refined and subsequently applied through the structured workflow. The research team retained responsibility for the extraction and classification framework and the resulting dataset. The characterization variables and their coded categories are summarized in Table 6.

Table 6. Characterization variables and coded categories.

Variable	Coded categories / description
Title, authors, author affiliations, year	Recorded as reported in the source document
Country, region/state/province	Location of the study or recommendation (not author affiliation)
Ontario relevance	Assigned via the four-level geographic tier classification (Table 7)
Study type	Field experiment; Greenhouse study; Lab study; Guidance/extension; Observational/diagnostic/testing study; Review; Editorial; Systematic review or meta-analysis
Document type	Original research article; Extension article/bulletin; Diagnostic/tissue-testing article; Review article; Commentary/editorial/news piece
Crop	Corn, soybean, corn + soybean, or corn/soybean with other crops
Micronutrient	Boron, chlorine, cobalt, copper, iron, manganese, molybdenum, nickel, zinc (records could report more than one)
Intervention method	Soil application; Foliar or leaf application; No intervention; Nano/advanced delivery; Seed treatment; Integrated nutrient management; Combined micronutrient + inoculant; Blend; Combined micronutrient + fungicide; Seed enrichment; Other
Outcome	Nutrient uptake; Yield; Biomass; Plant growth; Soil properties; Physiological response; Crop quality; Root traits; Diagnostic indicators; Microbial activity; Pest/disease response
Economic analysis reported	Yes / No
Geographic Tier	Tier 1, Tier 2, Tier 3, Tier 4
Ontario Relevance	High, Moderate, Low, None

Identifying Ontario-relevant records was important because findings from the international literature may not be directly transferable to Ontario corn and soybean production. Micronutrient availability and crop response are influenced by soil-forming history, climate and production systems. The geographic tier framework was therefore used to identify evidence generated under conditions with greater potential to inform Ontario interpretation and management.

Tier 1 (high relevance) included Laurentide-glaciated regions with temperate climates and corn or soybean systems directly comparable to Ontario. Tier 2 (moderate relevance) included largely glaciated, temperate regions with partial cropping-system similarity. Tier 3 (low relevance) included temperate regions with limited glacial-history or production-system similarity, while Tier 4 (no relevance) included tropical, subtropical, arid or highly weathered regions that were not considered comparable to Ontario conditions. Records in Tiers 1 and 2

underwent deeper extraction because they had greater potential for transfer to Ontario; this classification did not establish that every finding was directly applicable under Ontario conditions.

Table 7. Geographic tier classification and Ontario relevance.

Geographic Tier	Ontario Relevance	Criteria	Example Locations
Tier 1	High	Laurentide-glaciated; temperate climate; corn/soybean cropping system directly comparable to Ontario	Canada: Ontario, Quebec, Manitoba Red River Valley, eastern Saskatchewan, New Brunswick, Nova Scotia, PEI. U.S. Corn Belt: Minnesota, Wisconsin, Michigan, north/central Iowa, northern Illinois, Indiana, Ohio
Tier 2	Moderate	Largely glaciated; temperate climate; partial corn/soybean cropping-system overlap with Ontario	U.S. Northeast: New York, glaciated Pennsylvania, Vermont, New Hampshire, Maine. U.S. Northern Plains: North Dakota, South Dakota. Northern/Central Europe: United Kingdom, Ireland, northern Germany, Poland, Denmark, Netherlands, Baltic states
Tier 3	Low	Temperate climate but limited glaciation history or weaker cropping-system similarity to Ontario	France, Switzerland, Austria, northern China (temperate regions)
Tier 4	None	Tropical, subtropical, arid, or highly weathered soils; not comparable to Ontario conditions	Most of India, Brazil, Iran, Pakistan, Egypt, and other tropical, subtropical or arid regions

Records rated geographic tier 1 or Tier 2 (high or moderate Ontario relevance) underwent a second, more detailed extraction stage, capturing the additional variables summarized in Table 8, in addition to all characterization fields listed in Table 6.

Table 8. Deep-extraction variables, captured for geographic Tier 1-2 (high/moderate Ontario-relevant) records only.

Variable	Description
Application rate and timing	Rate and timing of micronutrient interventions
Soil characteristics	Soil type, texture class, taxonomic order/classification, pH range (minimum, maximum, mean), organic matter content
Soil test thresholds	Critical or sufficient soil levels for each of the nine micronutrients, plus the soil test method used
Plant tissue thresholds	Critical or sufficient plant tissue levels for each micronutrient, tissue type sampled, and crop growth stage at sampling
Economic analysis details	Economic metrics, units, currency, and price-year basis
Yield response	Absolute value and percentage, statistical significance, and categorical response type
Key insight	Brief statement summarizing the main finding
Study limitations	As reported in the source document

Data availability

The datasets supporting this systematic map are available as a downloadable Excel workbook on the [project website](#). The workbook contains three datasets: the full-text screening dataset, containing the records assessed during full-text screening (n=2,372); the full characterization dataset, containing the 1,365 records included in the systematic map and their extracted characteristics; and the Ontario-relevant subset, containing the 126 records classified as having high or moderate Ontario relevance and prioritized for deeper extraction. The full characterization dataset and Ontario-relevant subset include a unique Record ID for each record. Record IDs reported in Tables 11-18 correspond to records in the Ontario-relevant subset, allowing readers to locate the associated bibliographic and extracted information in the downloadable dataset.

Results and discussion

The results and discussion are organized around two levels of analysis. The search, screening and analytical datasets section reports the search and screening results and introduces the two analytical datasets. Part I uses the full characterization dataset (n = 1,365) to map the international knowledge landscape for micronutrients in corn and soybean production. Part II examines the Ontario-relevant subset (n = 126) (records rated as having high or moderate Ontario relevance and subject to deeper extraction) to assess the nature, depth and potential usefulness of knowledge relevant to Ontario production conditions. Because the datasets include peer-reviewed research as well as grey literature, including extension and advisory

guidance and industry information, the term *record* is used for individual items and *literature*, *available knowledge* or *body of knowledge* for collections of records.

Search, screening and analytical datasets

The searches identified 22,134 records from bibliographic databases and a further 261 through citation searching and grey-literature searches. After duplicate removal, 19,714 records underwent two rounds of title and abstract screening, of which 2,372 were assessed at full text. Full-text screening resulted in 1,365 records meeting the eligibility criteria and being included in the systematic map (Figure 1). Of these, 126 records met the high or moderate Ontario-relevance criteria and were prioritized for deeper extraction. The search and screening process is illustrated in the ROSES flow diagram (Figure 1), which summarizes the records identified, screened and included in the systematic map.

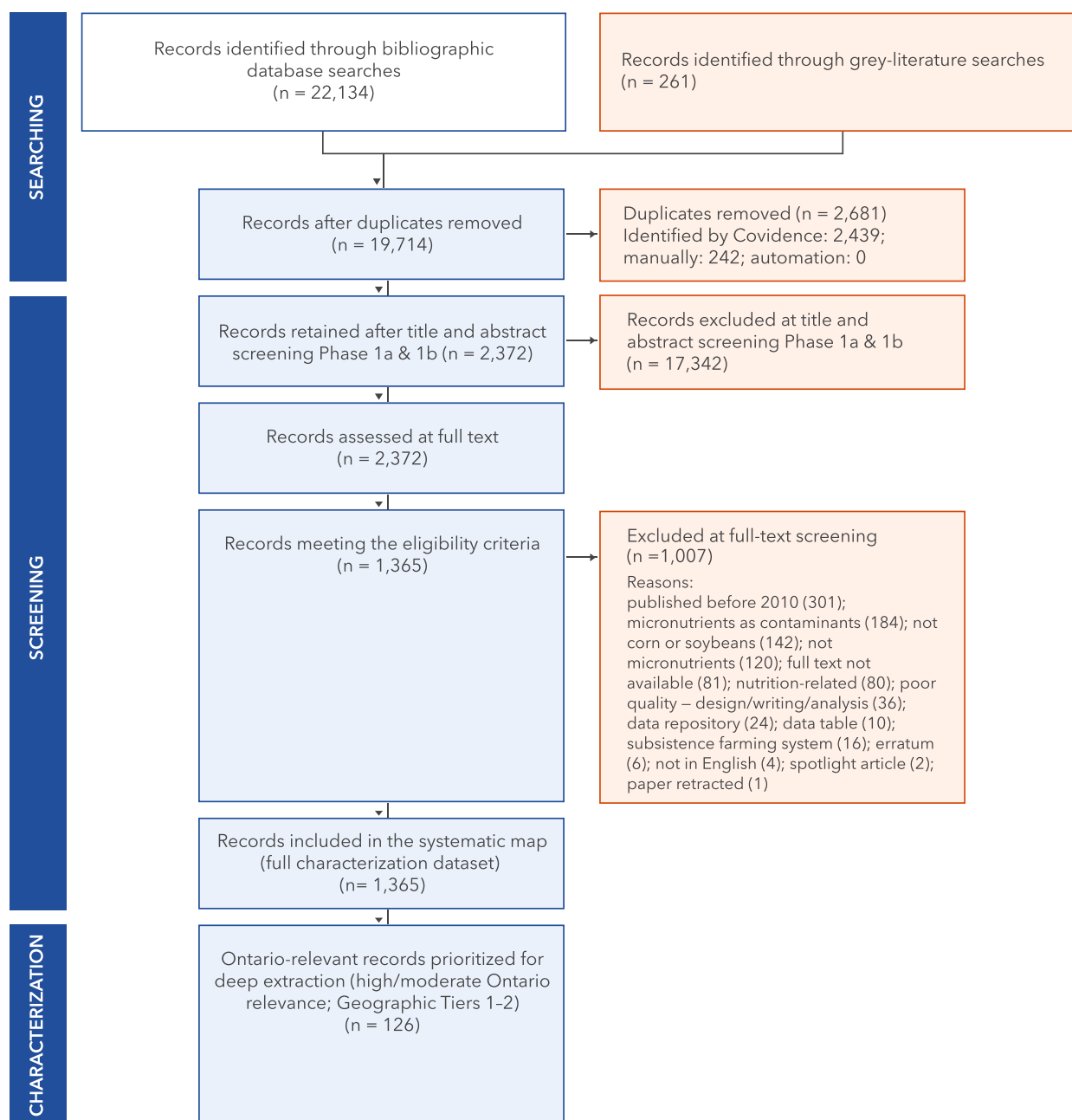


Figure 1. ROSES flow diagram showing the search and screening process and development of the full characterization dataset and Ontario-relevant subset. Adapted from the Reporting Standards for Systematic Evidence Syntheses (ROSES), version 1.0 (Haddaway et al. 2018).

Table 9. Overview of the full characterization dataset and the Ontario-relevant subset.

Metric	Full dataset (n = 1,365)	Ontario-relevant subset (n = 126)
Share of full dataset	100.0%	9.2%
Leading micronutrients (top 3)	Zinc, iron, manganese	Zinc, iron, manganese
Leading research approach	Field experiment – 46.8% (639)	Field experiment – 48.4% (61)
Guidance/extension material	6.1% (83)	23.0% (29)
Nutrient uptake reported	66.8% (912)	65.1% (82)
Yield reported	55.4% (756)	56.3% (71)
Soil properties reported	37.1% (506)	51.6% (65)
Diagnostic indicators reported	14.0% (191)	35.7% (45)
Economic analysis reported	6.9% (94)	4.8% (6)

The two datasets (full dataset, Ontario-relevant subset) share several defining characteristics. Applying the Ontario-relevance criteria substantially reduced the size of the available literature but did not change several of its dominant characteristics. Zinc, iron and manganese remained dominant, field experiments remained the leading research approach, and nutrient uptake and yield remained the most prominent outcomes.

At the same time, several differences point to a real change in the character of the knowledge once Ontario relevance is considered. Guidance and extension material nearly quadrupled in relative share, from 6.1% of the full dataset to 23.0% of the Ontario-relevant subset, and diagnostic indicators more than doubled, from 14.0% to 35.7%. Soil-property reporting also increased, from 37.1% to 51.6%. Economic analysis remained rare in both datasets, and was, if anything, less common within the Ontario-relevant subset (4.8% versus 6.9%). The Ontario-relevant subset retained a strong experimental foundation while containing a substantially larger relative contribution from applied guidance and diagnostic information.

These similarities and differences provide the rationale for treating the two datasets differently in the analyses that follow. Part I uses all 1,365 records to characterize the size, development, distribution and composition of the international micronutrient knowledge landscape. Part II does not repeat that characterization for the 126 Ontario-relevant records. Instead, it uses the Ontario-relevant subset and the deeper extraction to examine the composition, depth and management relevance of the knowledge having the most potential to inform Ontario corn and soybean production.

Part I — International micronutrient knowledge landscape

Part I addresses what the systematic map tells us about the overall state, distribution and development of knowledge on micronutrients in corn and soybean production.

Development of the micronutrient literature

Knowledge about micronutrients in corn and soybean production expanded substantially between 2010 and 2025 (Figure 2). The number of records published annually increased from 46 in 2010 to more than 70 per year by the middle of the decade, before increasing more rapidly after 2018. Annual publication exceeded 100 records in most years from 2020 onward, with the highest levels occurring in 2021 and 2023. Although publication activity fluctuated from year to year, including a decline in 2022, the longer-term pattern was one of considerable growth (Figure 2).

This growth indicates that micronutrient management in corn and soybean remained an active and expanding area of knowledge development over the 16-year period. Importantly, a substantial share of the mapped literature was produced during the latter part of the review period. The available knowledge was therefore not dominated by older research; it continued to develop as new research and other forms of information were published. The marked increase after 2018 also means that the overall size of the literature was shaped considerably by relatively recent activity.

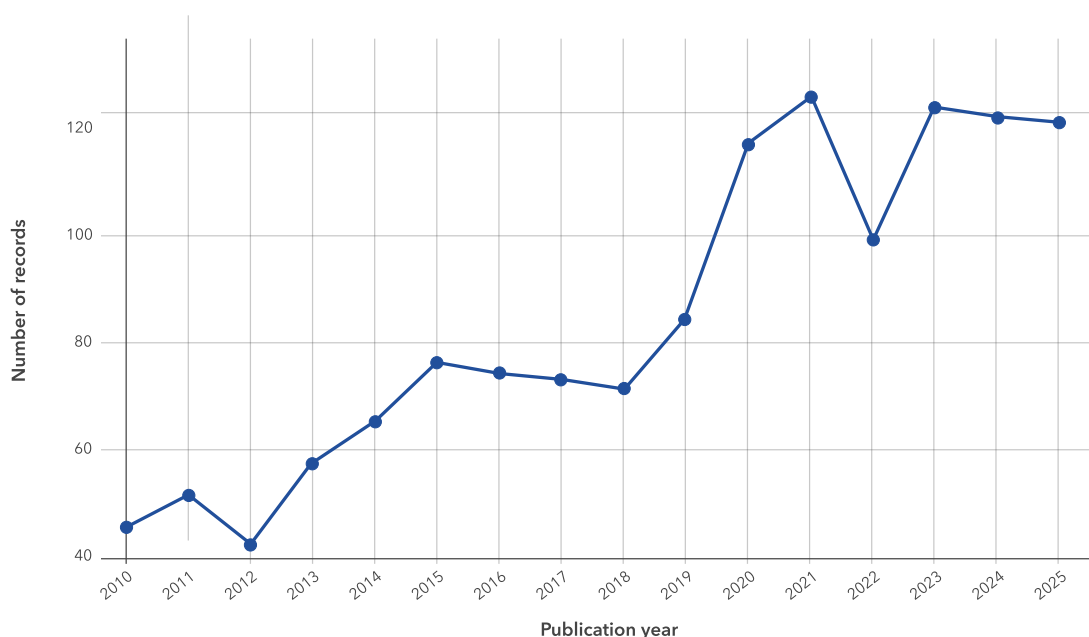


Figure 2. Number of records by publication year (full dataset)

Growth in publication volume, however, provides only one measure of how the knowledge landscape developed. A larger body of literature does not necessarily mean that knowledge expanded evenly across all nine micronutrients. Overall growth could reflect increasing attention to micronutrients that were already well represented, greater attention to previously

less-studied micronutrients, or some combination of the two. Understanding the development of micronutrient knowledge therefore requires considering not only how much literature was produced, but also where that research and information were concentrated.

The distribution of records among micronutrients provides the first indication of whether the expansion of the literature resulted in a broad body of knowledge or whether substantial differences in research attention persisted across micronutrients.

Distribution of knowledge among micronutrients and crops

Knowledge about micronutrients in corn and soybean production was distributed unevenly across the nine micronutrients (Figure 3). Zinc dominated the literature, appearing in almost two-thirds of all records (63.5%, $n = 867$). A second, well-represented group consisted of iron (37.7%), manganese (28.4%), boron (26.7%) and copper (23.4%). Beyond these five micronutrients, representation declined substantially. Molybdenum appeared in 10.5% of records, while nickel, cobalt and chlorine/chloride each occurred in fewer than 5% (Figure 3). Because individual records could address more than one micronutrient, these percentages were non-exclusive and did not sum to 100%

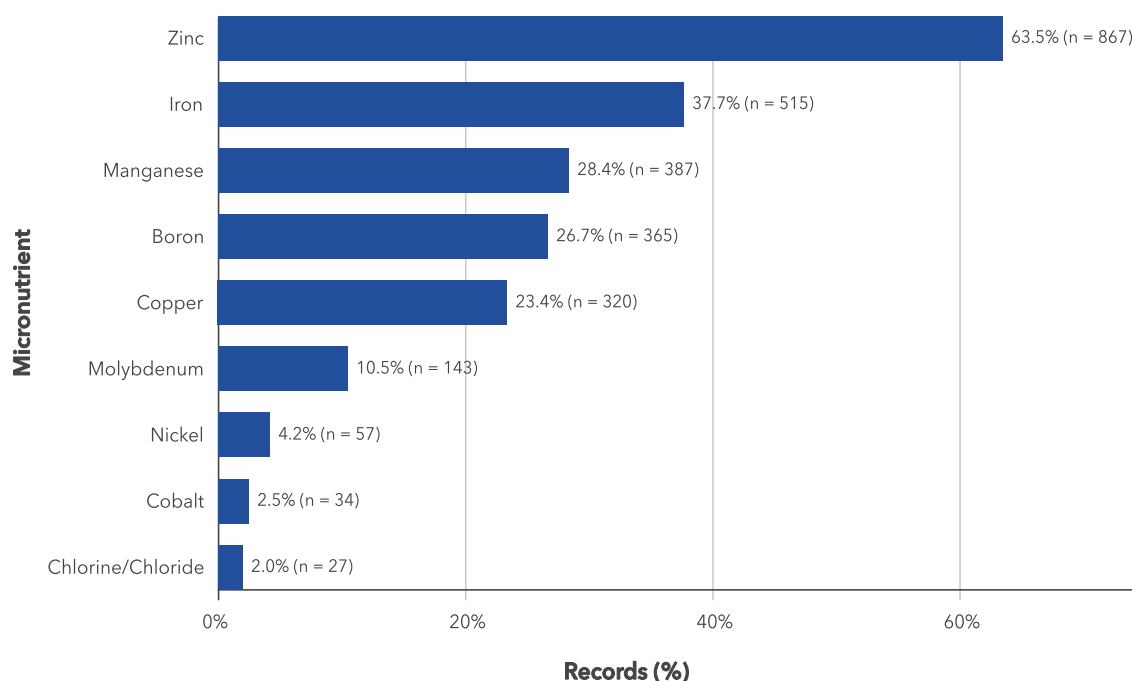


Figure 3. Records per micronutrient, as a percentage of the full dataset.

The size of the overall literature therefore masked substantial differences in the amount of knowledge available for individual micronutrients. Zinc had a particularly large body of literature, while iron, manganese, boron and copper also had substantial representation. In contrast, the much smaller numbers of records addressing molybdenum, nickel, cobalt and chlorine/chloride indicate considerably thinner areas of knowledge. These differences are

important because the ability to characterize micronutrient management, crop response and other aspects of the literature depends partly on how much information is available for each micronutrient. A large overall literature does not necessarily provide comparable knowledge across all nine micronutrients.

Crop-specific patterns add another dimension to this uneven knowledge landscape (Figure 4). Zinc's overall dominance was driven particularly by its strong representation in corn: 594 records addressed zinc in corn compared with 320 in soybean. In contrast, iron, manganese, boron and copper were more evenly represented across the two crops. Iron appeared in 260 corn and 282 soybean records, while manganese and boron had nearly equal representation in the two crops (Figure 4). This suggests that the comparatively substantial knowledge available for these micronutrients was not confined primarily to one of the two major crops.

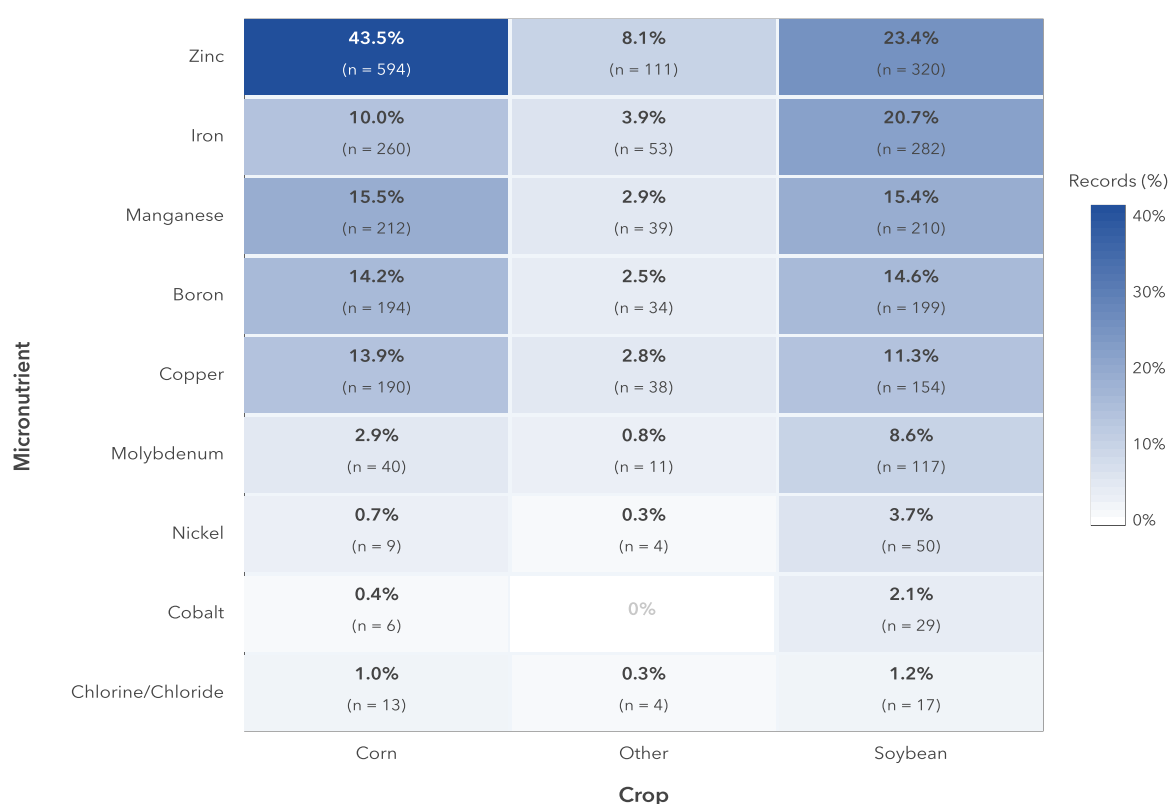


Figure 4. Micronutrient by crop, as a percentage of the full dataset.

The smaller bodies of knowledge showed a different pattern. Molybdenum and nickel were much more strongly represented in soybean than in corn. Molybdenum appeared in 117 soybean records compared with 40 corn records, while nickel appeared in 50 soybean records but only nine corn records. Cobalt was also concentrated in soybean, with 29 soybean records compared with six for corn. Chlorine/chloride differed from this pattern: although it was poorly represented overall, the small number of records was more evenly divided between corn and soybean. Thus, limited knowledge about a micronutrient did not

necessarily mean that the gap was equally distributed between crops. For molybdenum, nickel and cobalt, the knowledge limitation was particularly pronounced for corn.

Taken together, the micronutrient and crop distributions reveal several distinct concentrations in the international knowledge landscape. Zinc was both the most extensively represented micronutrient overall and particularly prominent in corn. Iron, manganese, boron and copper formed a second group with substantial knowledge across both corn and soybean. Molybdenum, nickel and cobalt were much less represented overall and were more strongly associated with soybean, while chlorine/chloride had little representation for either crop. The literature therefore varied not only in the amount of knowledge available for each micronutrient, but also in how that knowledge was distributed between corn and soybean.

These imbalances have implications for the remainder of the systematic map. Areas with large and crop-diverse bodies of literature provide a broader foundation for examining research approaches, management interventions and outcomes. For micronutrients represented by relatively few records—or where knowledge is concentrated in one crop—the conclusions that can ultimately be drawn are necessarily more limited. This becomes particularly important when the international literature is subsequently narrowed to knowledge relevant to Ontario. Crop composition is reported in Supplementary Table S1; the more important finding here is the uneven distribution of micronutrient knowledge within and between the two crops.

The next question is therefore not simply how much knowledge exists, but what kinds of research and information have generated that knowledge. The following section examines the research approaches represented across the literature.

Research approaches and intervention methods

Knowledge about micronutrients in corn and soybean production was generated predominantly through original experimental research (Figure 5). Field experiments were the most common research approach, accounting for 46.8% of the full dataset (639 records), followed by greenhouse studies (27.0%, 368) and laboratory studies (15.3%, 209) (Figure 5). Together, these approaches show that much of the available knowledge was generated through direct observation and measurement of micronutrient effects under field or controlled experimental conditions.

The prominence of field experiments is particularly important for understanding the nature of the knowledge captured by the map. Field research provides information on micronutrient behaviour and crop response under production conditions, while greenhouse and laboratory studies allow micronutrient processes and responses to be examined under more controlled conditions. The substantial representation of all three approaches means that the international literature contains both production-oriented and controlled experimental research. The systematic map did not assess the quality or strength of individual records, however, so the number of experimental records should not be interpreted as a measure of the effectiveness of particular micronutrient practices.

Applied guidance and other forms of synthesized or diagnostic information made up a much smaller part of the literature. Guidance and extension documents accounted for 6.1% of records, while observational/diagnostic/testing studies represented 2.6%. Reviews, editorials and systematic reviews or meta-analyses were comparatively uncommon. The international knowledge landscape was therefore weighted much more heavily toward the generation of primary research than toward synthesis, diagnostic assessment or applied guidance. This distinction is important because these different types of information serve different purposes: experimental research can establish crop and nutrient responses under specified conditions, while synthesis, diagnostic and guidance materials help bring findings together and make them more directly usable for interpretation and management.

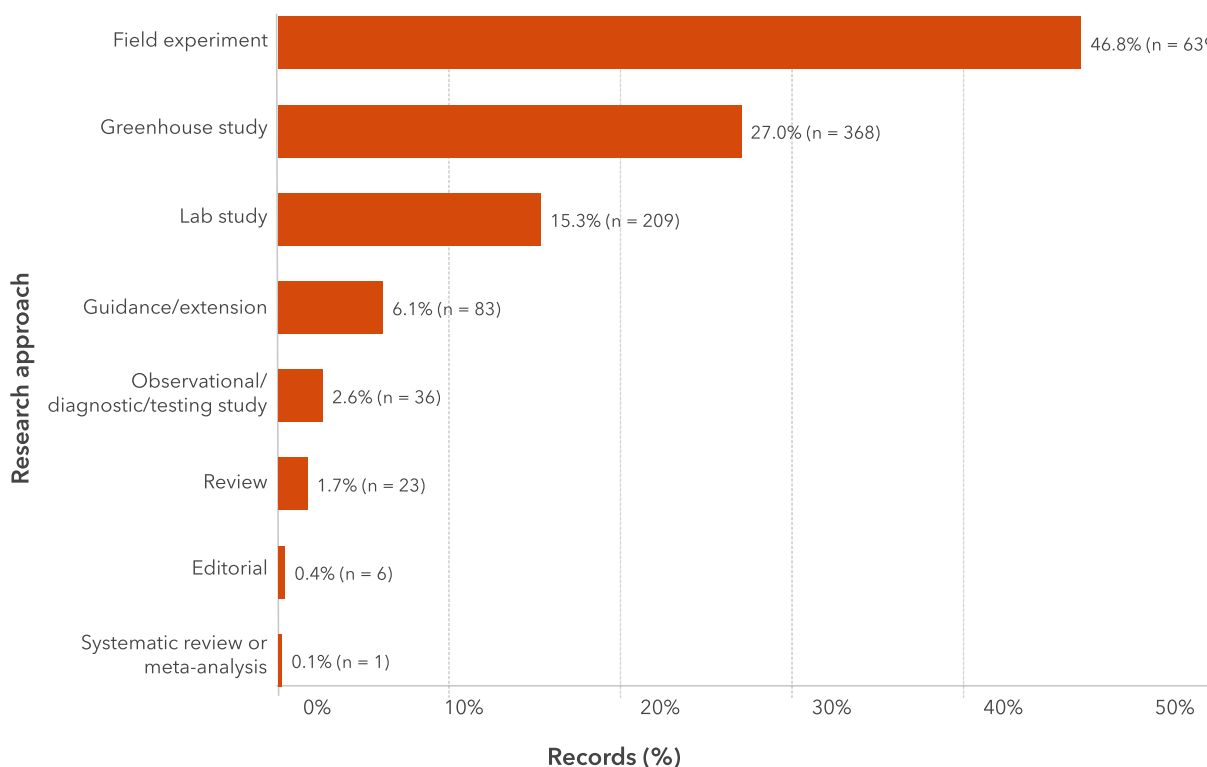


Figure 5. Research approach, as a percentage of the full dataset.

The intervention methods represented in the literature provide additional context for the experimental orientation of the knowledge base. Soil and foliar applications were the most frequently represented intervention methods, accounting for 34.3% and 26.7% of records, respectively, while 22.7% involved no applied micronutrient intervention (Figure 6). The presence of a substantial group of records without an intervention is also important: micronutrient knowledge was not generated solely through fertilizer-response experiments. The literature also included work concerned with micronutrient status, availability, diagnosis and other questions that did not require an applied treatment.

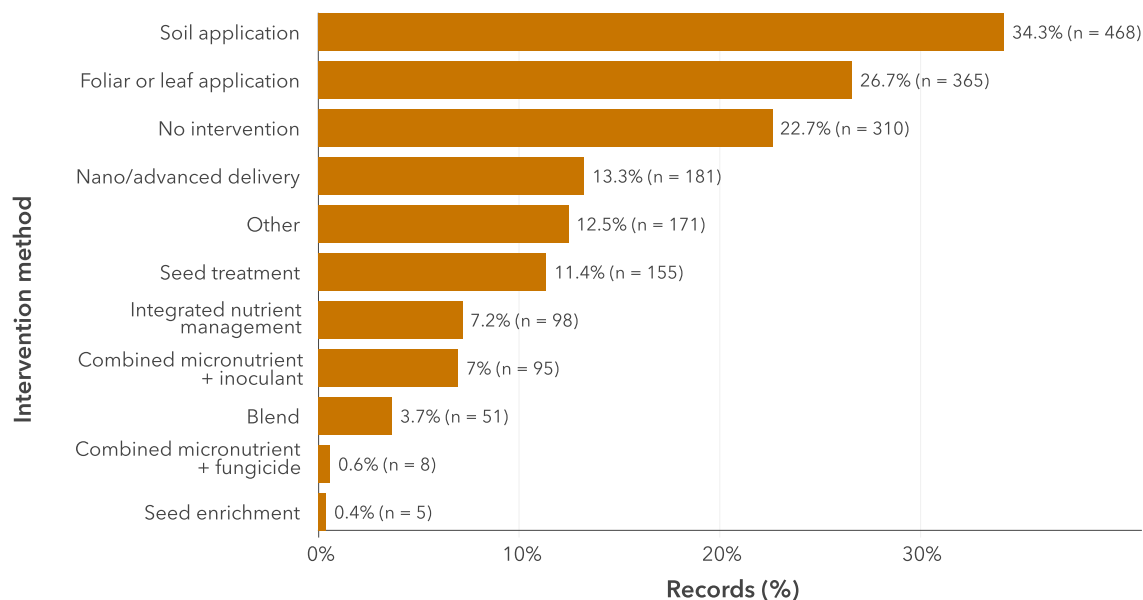


Figure 6. Intervention methods, as a percentage of the full dataset. Soil application (34.3%, 468) and foliar application (26.7%, 365) are the leading methods; no-intervention records account for 22.7% (310); nano/advanced-delivery formulations (13.3%, 181), other unclassified interventions (12.5%, 171) and seed treatments (11.4%, 155) follow.

Taken together, the distribution of research approaches shows that the international micronutrient literature provides a substantial experimental foundation, particularly from field research, but a much smaller body of synthesized, diagnostic and applied guidance. This composition affects the kinds of questions the literature is positioned to answer. A large experimental literature can provide extensive information about micronutrient responses and processes, but the usefulness of that knowledge for management also depends on what outcomes were measured. The next section therefore examines the outcomes represented across the literature to determine which dimensions of micronutrient response have been investigated most extensively and which have received comparatively little attention.

Outcomes addressed in the literature

The outcomes assessed in the literature provide an important indication of what is known about micronutrients in corn and soybean production. Outcomes determine which effects of micronutrient status or management have been measured and, consequently, the kinds of questions the available knowledge can help answer. They are particularly important for understanding whether the literature addresses crop response and productivity, the processes underlying those responses, and the diagnostic information needed to support management decisions.

The international literature was strongly oriented toward crop nutrition, productivity and growth. Nutrient uptake was the most frequently assessed outcome, appearing in 66.8% of records, while yield was assessed in 55.4%. Biomass and plant growth were each examined in almost half of the records (49.6% and 47.4%, respectively) (Figure 7). Together, these

outcomes indicate that a substantial portion of micronutrient knowledge addresses two closely related questions: how crops acquire and respond to micronutrients, and whether those responses translate into changes in crop growth and productivity.

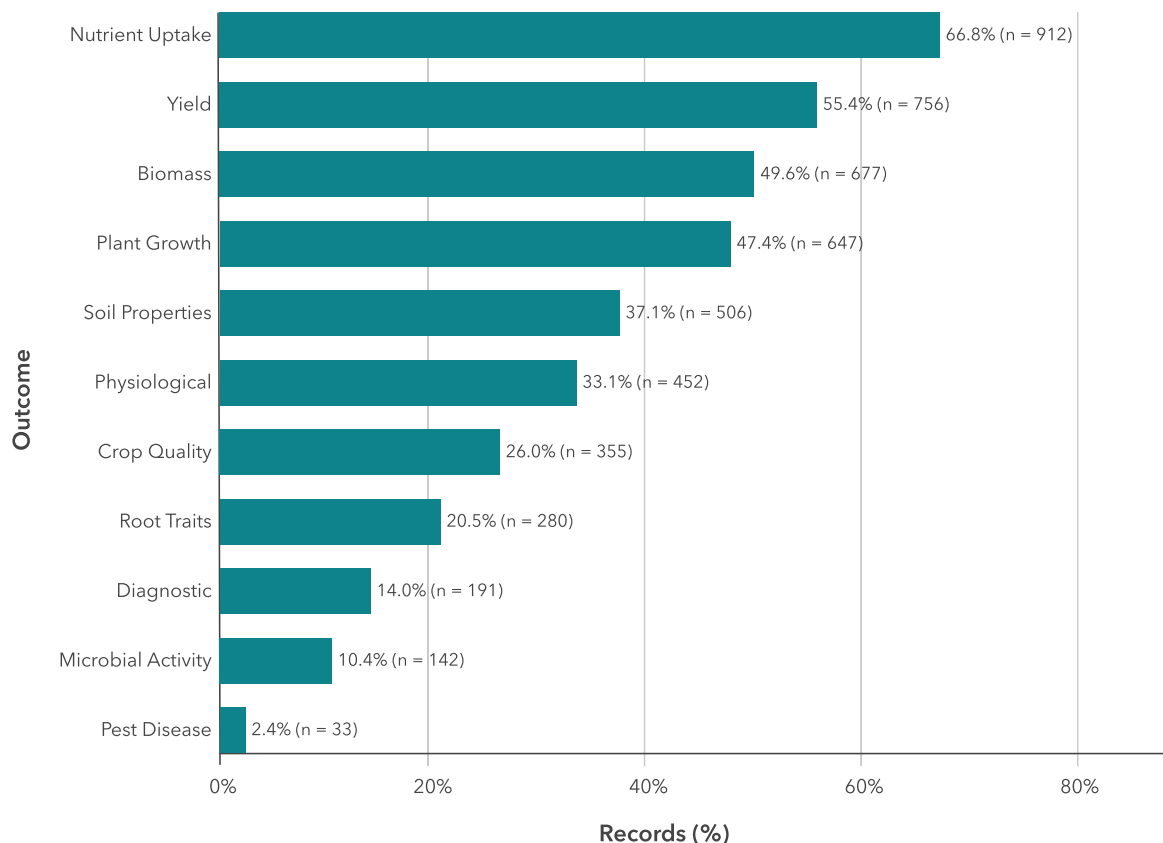


Figure 7. Outcomes assessed as a percentage of the full dataset.

A second group of outcomes provides information about the soil and plant processes associated with micronutrient response. Soil properties were assessed in 37.1% of records and physiological outcomes in 33.1%, while root traits were examined in 20.5%. Crop quality was assessed in approximately one-quarter of the literature (26.0%). These outcomes broaden the knowledge landscape beyond yield response by providing information about the conditions and biological processes through which micronutrients may influence crop performance. At the same time, their lower representation means that the literature provides less extensive knowledge about these dimensions than it does about nutrient uptake, yield and crop growth.

Some types of knowledge that are particularly relevant to identifying micronutrient problems and understanding broader biological responses were much less developed. Diagnostic indicators were assessed in 14.0% of records and microbial activity in 10.4%, while pest and disease outcomes appeared in 2.4%. The comparatively limited representation of diagnostic outcomes is notable because decisions about micronutrient management depend not only

on knowing whether an intervention can affect crop performance, but also on being able to identify when micronutrient status may warrant intervention.

The breadth of outcome knowledge also differed among micronutrients. Zinc was represented across the widest range of outcomes, while iron, manganese, boron and copper also had comparatively broad outcome coverage, particularly for nutrient uptake and yield. Molybdenum was represented across a narrower range of agronomically important outcomes, and knowledge about nickel, cobalt and chlorine/chloride was limited across most outcome categories (Figure 8). This pattern reinforces the unevenness identified in the preceding distribution analysis: micronutrients with smaller bodies of literature generally also have fewer types of outcomes represented. Their knowledge gaps therefore involve not only fewer records, but also a narrower range of questions that the available literature can address.

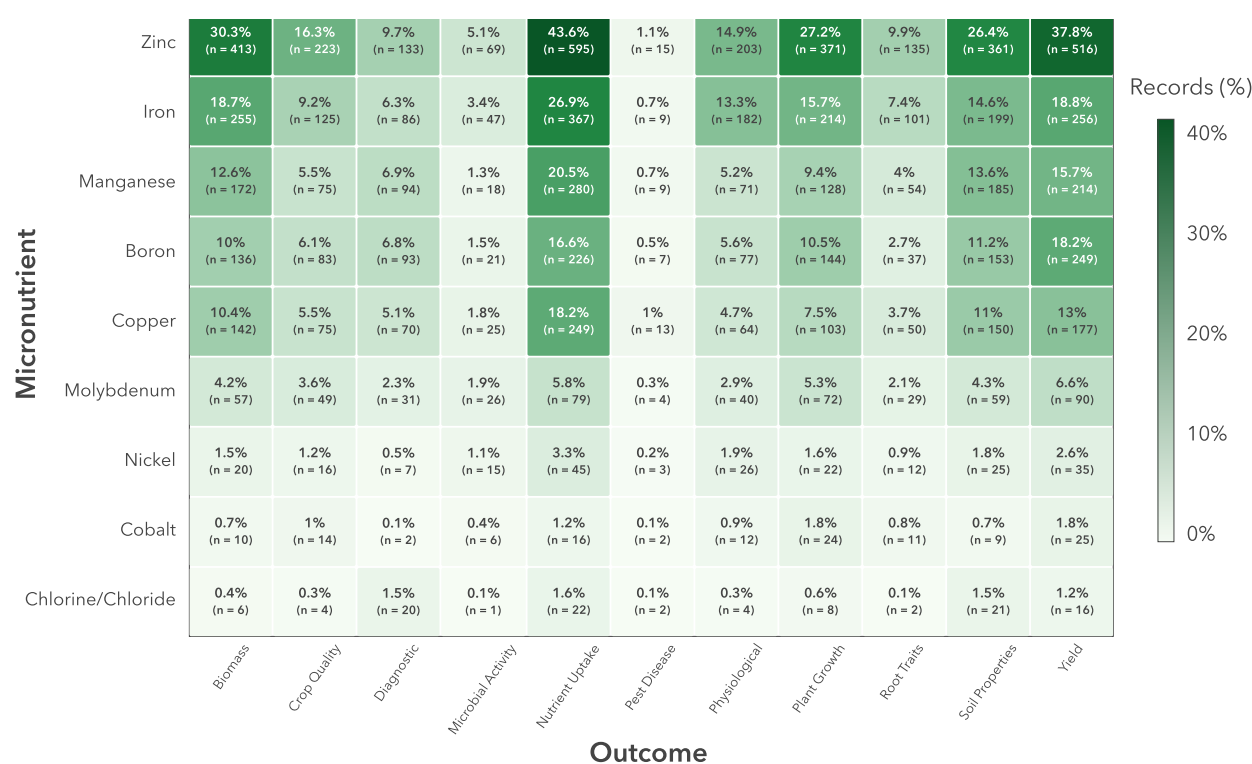


Figure 8. Micronutrient by outcome, as a percentage of the full dataset. Zinc has the broadest outcome coverage; iron, manganese, boron and copper are examined across a reasonably wide range of outcomes; nickel, cobalt and chlorine have limited coverage across nearly every outcome category.

Taken together, the outcome profile shows that the international literature provides substantial knowledge about micronutrient uptake, crop growth and agronomic performance, supported by a smaller body of information on soil properties, physiology, crop quality and root responses. Knowledge related to diagnosis, microbial processes and pest and disease responses is considerably less extensive. The systematic map therefore reveals an imbalance not simply in how much micronutrient literature exists, but also in what that

literature can tell us. Because individual records could assess more than one outcome, outcome categories were non-exclusive and percentages did not sum to 100%.

The next question is whether this distribution of knowledge has remained stable as the literature has grown. The following section examines changes in the relative attention given to individual micronutrients over time to determine whether the expansion of the literature has broadened the knowledge landscape or whether longstanding concentrations have persisted.

Changes in micronutrient research focus over time

The substantial growth in micronutrient literature described earlier did not occur evenly across the nine micronutrients. Some longstanding concentrations of knowledge persisted throughout 2010–2025, while the relative representation of several micronutrients changed over time. Figure 9 shows the percentage of records published in each year that addressed each micronutrient. These percentages indicate how research attention was distributed within a given year and need to be interpreted alongside the substantial increase in the total number of records published annually over the same period.

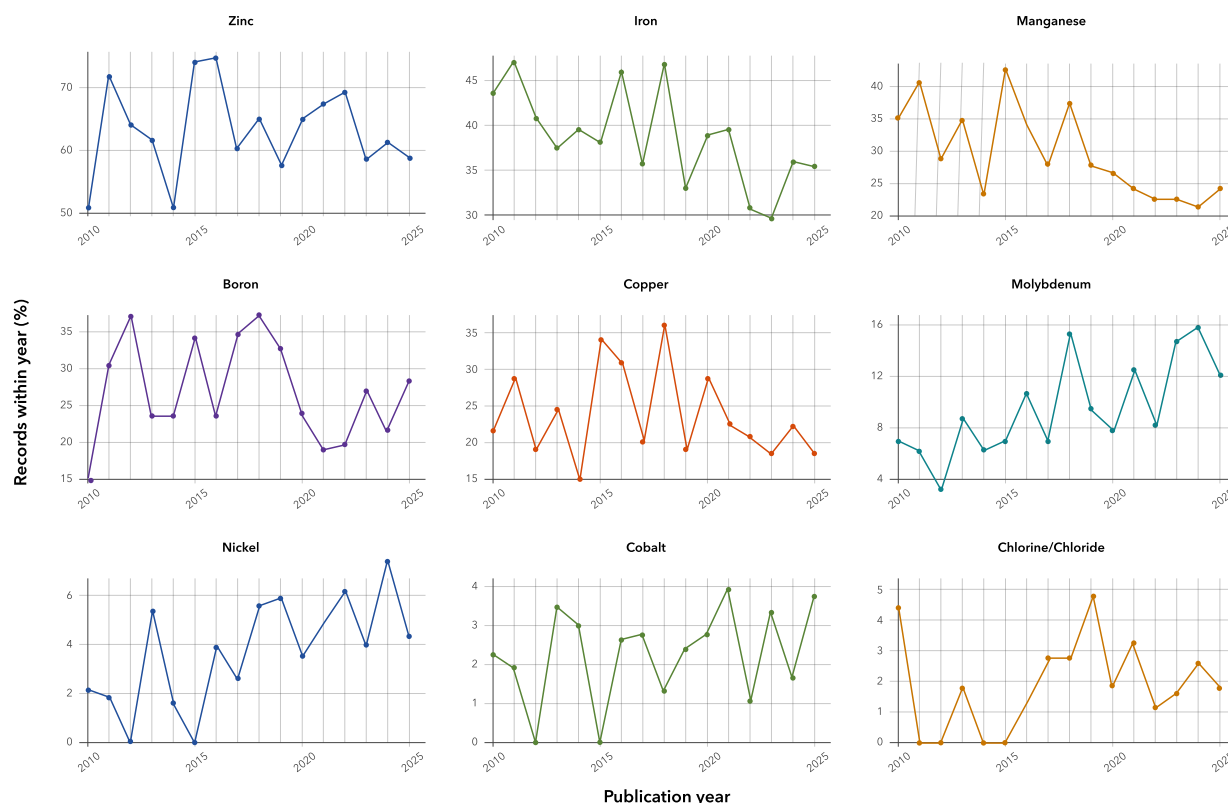


Figure 9. Micronutrient trends by publication year, shown separately for each micronutrient as a percentage of records published each year (full dataset).

Zinc remained the dominant micronutrient throughout the 16-year period. It appeared in at least half of the records published every year and generally accounted for about 60% or

more of annual records. Although its share fluctuated, there was no sustained upward or downward trend. When considered alongside the increase in total annual publications, this sustained proportional representation indicates that the amount of literature addressing zinc also grew substantially. The expansion of the overall knowledge landscape therefore did not reduce the strong concentration of knowledge around zinc.

Iron, manganese, boron and copper also remained substantial components of the literature, but their temporal patterns differed. Iron's share was generally lower in recent years than at several earlier peaks, while manganese declined from approximately 30–40% of annual records in several earlier years to about 20–25% in more recent years. Copper showed a broadly similar reduction in relative representation, whereas boron fluctuated without a clear long-term direction. These declining percentages should not be interpreted as evidence that the absolute amount of research on iron, manganese or copper necessarily decreased. Because considerably more records were being published annually later in the review period, a micronutrient could account for a smaller share of a larger annual literature while still being represented by as many or more records. The patterns instead indicate that these micronutrients occupied a smaller relative share of the expanding knowledge landscape in recent years.

Molybdenum and nickel showed the clearest evidence of increasing relative representation. Molybdenum generally accounted for less than 10% of annual records during the earlier part of the period but reached approximately 12–15% in several recent years. Nickel remained much less represented overall, but its annual share also increased from very low levels early in the period to approximately 4–7% in several recent years. Combined with the increase in the overall volume of literature, these patterns indicate some broadening of the knowledge landscape toward micronutrients that had previously accounted for relatively small shares of published records. However, neither approached the volume of knowledge available for the five most extensively represented micronutrients.

Cobalt and chlorine/chloride remained sparsely represented throughout the period. Each generally accounted for less than 5% of annual records and neither showed a sustained increase in relative representation. These trends should be interpreted particularly cautiously because the percentages are based on small numbers of records. Even relatively large year-to-year changes in percentage can result from the addition or absence of only a few records. More importantly, the substantial overall growth of the micronutrient literature did not produce a comparable expansion in knowledge for these two micronutrients.

Taken together, the temporal patterns show that growth in the international literature produced some broadening of micronutrient knowledge but did not fundamentally rebalance the knowledge landscape. Zinc maintained its dominant position, while iron, manganese, boron and copper continued to account for substantial portions of the literature. Molybdenum and nickel increased their relative representation, suggesting that the expansion of the literature extended to some previously less-represented micronutrients. In contrast, cobalt and chlorine/chloride remained minor areas despite the considerable

increase in micronutrient research and information overall. The knowledge gaps identified from the aggregate record counts reported in the distribution analysis were therefore not simply a consequence of earlier publication patterns; important differences in the amount of attention given to individual micronutrients persisted through the most recent years covered by the map.

The expansion and changing composition of the literature establish how micronutrient knowledge developed over time, but they do not establish how readily that knowledge can be applied to Ontario. The geographic distribution of the literature is particularly important in this regard. The following section therefore examines where micronutrient knowledge was generated and what that distribution means for its potential transferability to Ontario corn and soybean production.

Geographic distribution and transferability of knowledge

The international micronutrient literature was geographically broad, but much of the available knowledge was generated under production conditions that differ substantially from those in Ontario (Figure 10).¹ This matters because micronutrient availability and crop response are influenced by soil characteristics, climate, cropping systems and management practices. Knowledge generated in one region therefore cannot necessarily be assumed to transfer directly to another, making geographic and production context an important consideration when assessing the relevance of the international literature to Ontario corn and soybean production.

¹ The geographic information also had an important limitation: country was missing for 205 records (15.0%). This was a substantial proportion of the mapped literature and meant that the geographic distribution could not be determined for all records.

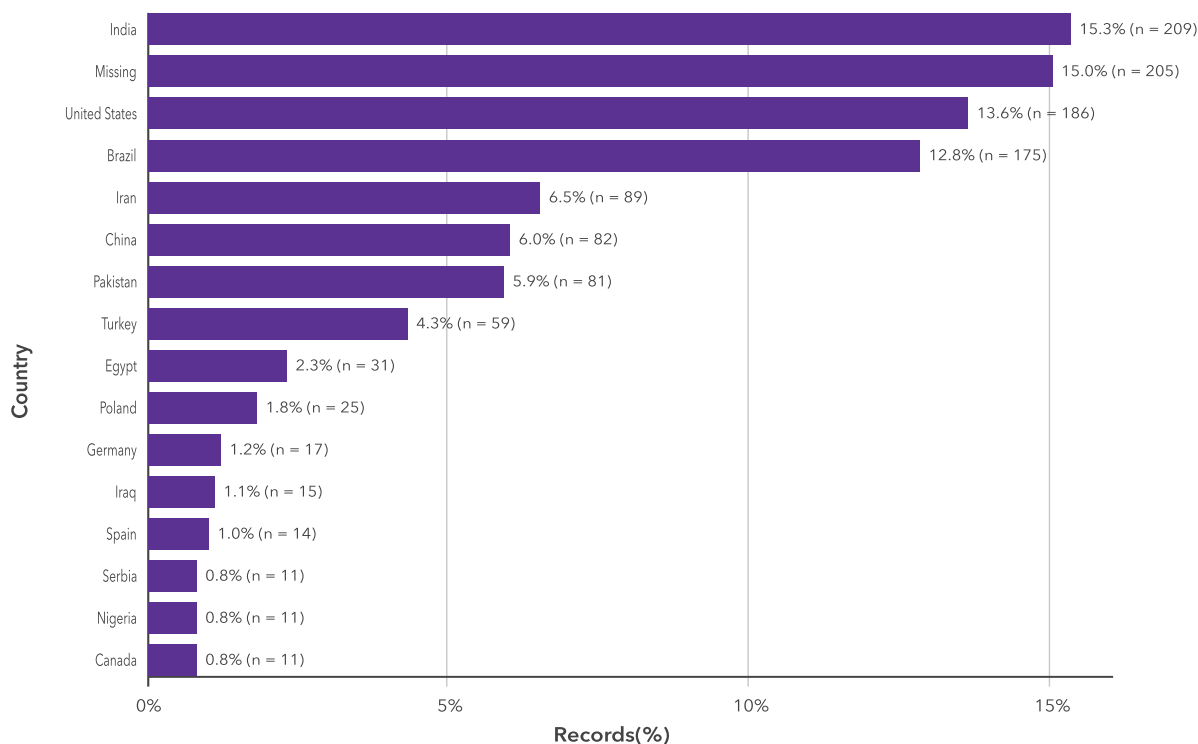


Figure 10. Top 15 countries represented in the full dataset, ranked by percentage of records. Bar labels show the percentage of the full dataset, with the number of records in brackets.

The literature was concentrated in several major agricultural regions outside Canada. India was the most frequently represented country, accounting for 15.3% of the full dataset (209 records), followed by the United States (13.6%, 186 records) and Brazil (12.8%, 175 records). Iran, China and Pakistan also contributed substantial numbers of records (Figure 10). At a regional level, this resulted in strong representation from South Asia, together with substantial contributions from other tropical, subtropical and arid production environments. The United States was the largest source of knowledge from temperate North America, while only 11 records (0.8%) originated in Canada.

The geographic distribution therefore creates an important distinction between the size of the international literature and the amount of knowledge potentially transferable to Ontario. The 1,365 records provide a substantial international knowledge landscape, but much of that literature was generated in production environments that differ from Ontario's glaciated, temperate conditions. Findings from these regions may still contribute to understanding micronutrient processes and crop responses, but their direct relevance to Ontario management cannot be determined from the existence of the research alone. The environmental and production conditions under which the knowledge was generated also need to be considered.

At the same time, geographic distance should not be treated as equivalent to lack of relevance. Research conducted outside Ontario—and outside Canada—can provide valuable

information when the underlying production environment shares important characteristics with Ontario. Similarities in continental glaciation history, temperate climate, soils and corn and soybean cropping systems can make findings from other regions potentially transferable even when they originate in another country. Conversely, geographic proximity alone does not establish that findings are directly applicable. The relevant question is therefore not simply where the research was conducted, but how comparable its production environment is to Ontario. This distinction provided the rationale for the geographic tier framework used to identify records for deeper extraction.

The geographic pattern also highlights an important feature of the knowledge available to Ontario. With only a small number of records generated in Canada, assessment of micronutrient management cannot depend solely on Canadian research. The broader international literature substantially expands the pool of potentially useful knowledge, but it also makes systematic assessment of transferability essential. The geographic tier framework addresses this challenge by narrowing the international literature to records generated under conditions considered sufficiently comparable to Ontario to warrant deeper examination. Importantly, classification as Ontario-relevant indicates greater potential for transferability; it does not establish that every finding can be applied directly to Ontario production conditions.

This distinction marks the transition from the international knowledge landscape to the second part of the systematic map. Part I showed that micronutrient knowledge has expanded considerably but remains unevenly distributed among micronutrients, crops, outcomes and geographic regions. Part II asks a different question: when the international literature is filtered for relevance to Ontario, what knowledge remains, where does it come from, and how well developed is it? The 126 records classified as having high or moderate Ontario relevance provide the basis for that analysis.

Part II – Ontario-relevant micronutrient knowledge

Part II tells us about the nature, depth and potential usefulness of micronutrient knowledge for Ontario corn and soybean production.

Applying the Ontario-relevance criteria substantially narrowed the international literature, from 1,365 records to 126 records rated as high or moderate relevance. This reduction of more than 90% reinforces the distinction between the overall size of the international literature and the much smaller body of knowledge generated under environmental and production conditions considered sufficiently comparable to Ontario. The Ontario-relevant literature was therefore not simply a smaller version of the full dataset; it represented a deliberately selected body of knowledge with greater potential for transfer to Ontario corn and soybean production.

Geographic sources of Ontario-relevant knowledge

Most of the knowledge identified as potentially relevant to Ontario was generated outside Canada. The United States accounted for more than half of the Ontario-relevant records (56.3%, $n = 71$), followed by Poland (19.8%, $n = 25$) and Germany (13.5%, $n = 17$). Canada contributed only five records (4.0%), with smaller contributions from Slovakia, Denmark, the Czech Republic and Hungary (Figure 11).

This geographic distribution substantially expanded the amount of knowledge potentially available to inform micronutrient management in Ontario. Canadian research alone provided a very small knowledge base, whereas including research from regions with comparable glaciation history, temperate climates and corn and soybean production systems identified a much larger body of potentially relevant information. Research from the U.S. Corn Belt and parts of northern and central Europe therefore represents an important source of knowledge for Ontario.

At the same time, the geographic pattern means that Ontario relies heavily on knowledge transferred from other production environments. Classification as high or moderate Ontario relevance identified records generated under broadly comparable conditions, but it did not establish that individual findings were directly applicable to Ontario. Differences in soils, climate, cropping practices and other local conditions can affect micronutrient availability and crop response. The Ontario-relevant subset should therefore be understood as a body of knowledge with greater potential for transfer to Ontario, rather than as evidence generated specifically under Ontario conditions.

The geographic analysis consequently reveals both an opportunity and a limitation. Research from comparable regions considerably increases the knowledge available to Ontario, but the small Canadian contribution increases the importance of determining whether individual findings are transferable to specific Ontario production conditions. The usefulness of this knowledge therefore depends not only on where it was generated, but also on how well the underlying production context is characterized and how closely it corresponds to Ontario conditions.

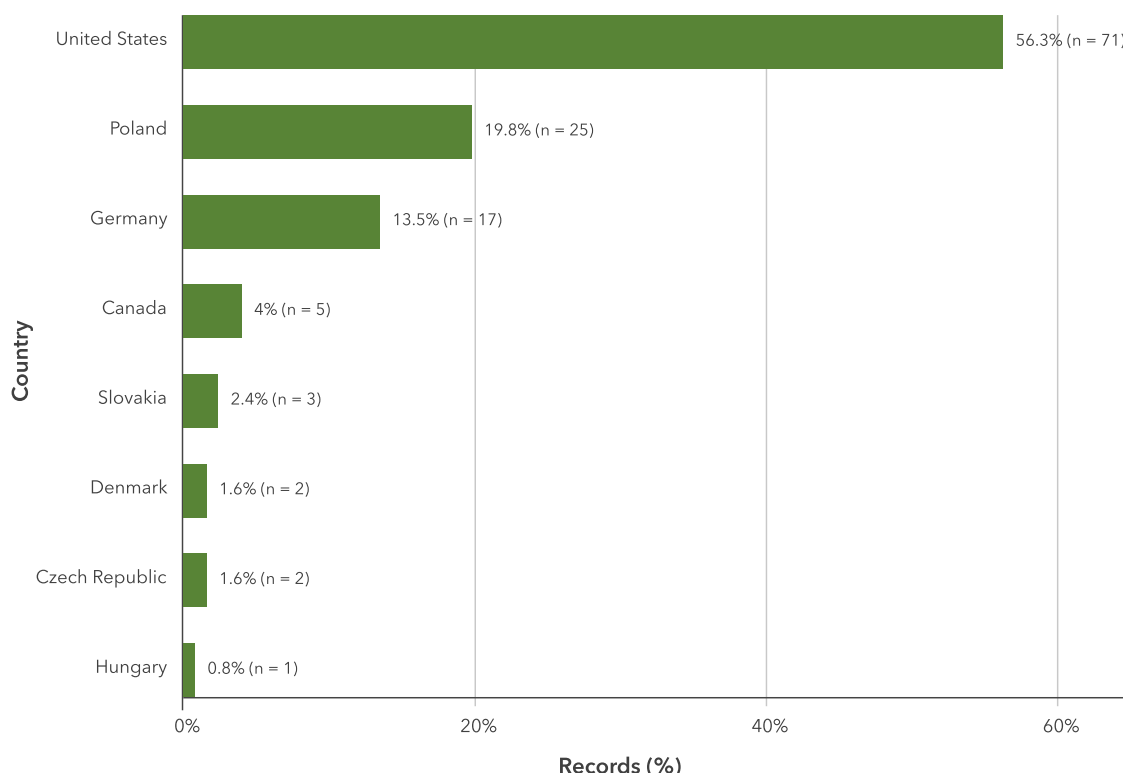


Figure 11. Top countries represented in the Ontario-relevant subset, ranked by percentage of records. Bar labels show the percentage of the Ontario-relevant subset, with the number of records in brackets.

Composition and depth of Ontario-relevant knowledge

The Ontario-relevant knowledge was uneven not only in the number of records available for individual micronutrients, but also in the types of research and applied information represented. Knowledge depth was therefore considered in terms of both the volume of records and the diversity of research approaches available for each micronutrient. These characteristics describe the size, breadth and composition of the mapped knowledge; they do not indicate evidence quality, consistency of findings or readiness for recommendation.

The amount of Ontario-relevant knowledge varied substantially among the nine micronutrients (Figure 12). Zinc had the largest body of knowledge (63.5%, $n = 80$), followed by iron (54.0%, $n = 68$) and manganese (51.6%, $n = 65$). Copper (35.7%, $n = 45$) and boron (33.3%, $n = 42$) also had substantial representation, after which the amount of available knowledge declined sharply. Molybdenum was represented by 17 records (13.5%), chlorine/chloride by eight (6.3%), nickel by three (2.4%) and cobalt by only two (1.6%). The Ontario-relevance criteria therefore did not fundamentally rebalance the micronutrient knowledge landscape: micronutrients that were well represented internationally generally remained well represented in the Ontario-relevant subset, while those with relatively small international literatures continued to have limited Ontario-relevant knowledge.

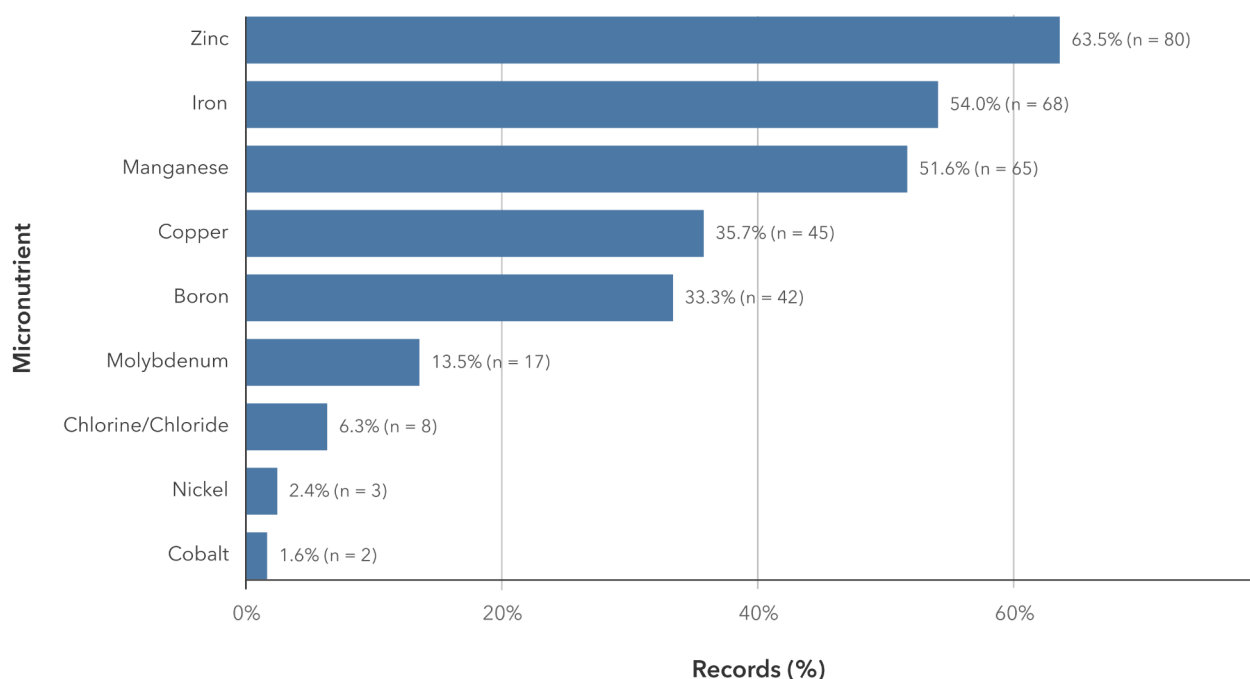


Figure 12. Records per micronutrient, as a percentage of the Ontario-relevant subset.

The composition of this knowledge was also important. Almost half of the Ontario-relevant records were field experiments (48.4%, $n = 61$), a proportion similar to the full dataset (46.8%). At the same time, guidance and extension material accounted for 23.0% of the Ontario-relevant subset, compared with only 6.1% of the international dataset (Figure 13). The Ontario-relevant knowledge therefore combined a substantial experimental foundation with a much stronger applied component than was evident in the international literature overall. This applied material adds information intended to support interpretation and production decisions, but the map did not examine whether individual guidance documents were derived from or translated the experimental research contained in the dataset.

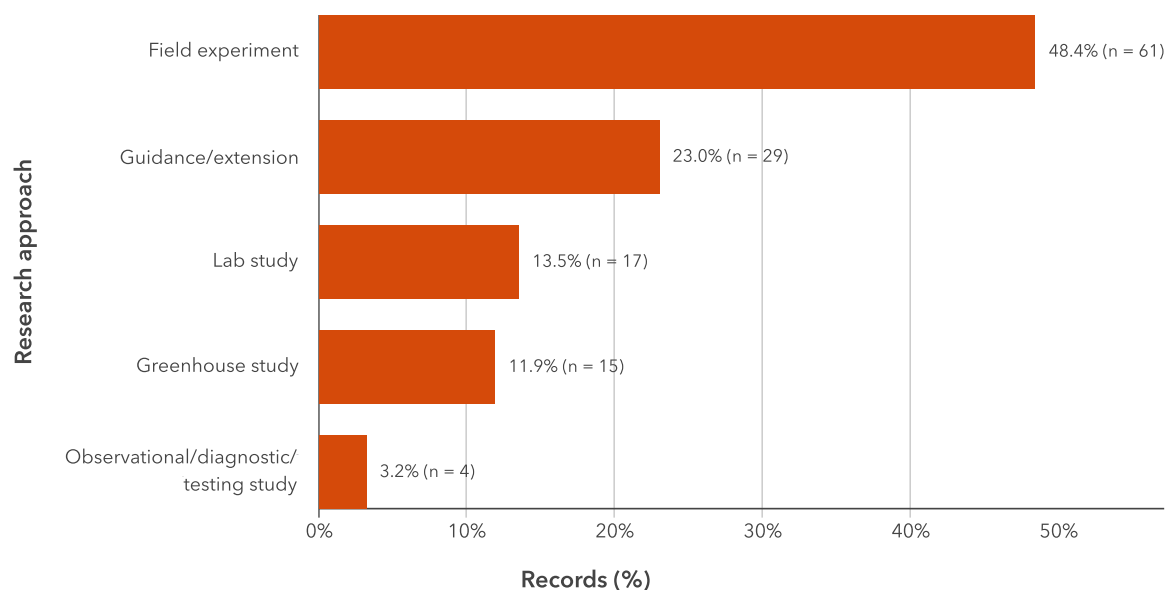


Figure 13. Research approach, as a percentage of the Ontario-relevant subset.

Considering record volume and research approach together identified a clear gradient in the depth of knowledge available for individual micronutrients (Figure 14). Zinc, iron, manganese, copper and boron combined comparatively large record totals with multiple forms of knowledge, including field, greenhouse and laboratory research as well as guidance. These micronutrients therefore had the broadest Ontario-relevant knowledge foundations. Molybdenum occupied an intermediate position: both experimental and applied information were available, but from a substantially smaller number of records.

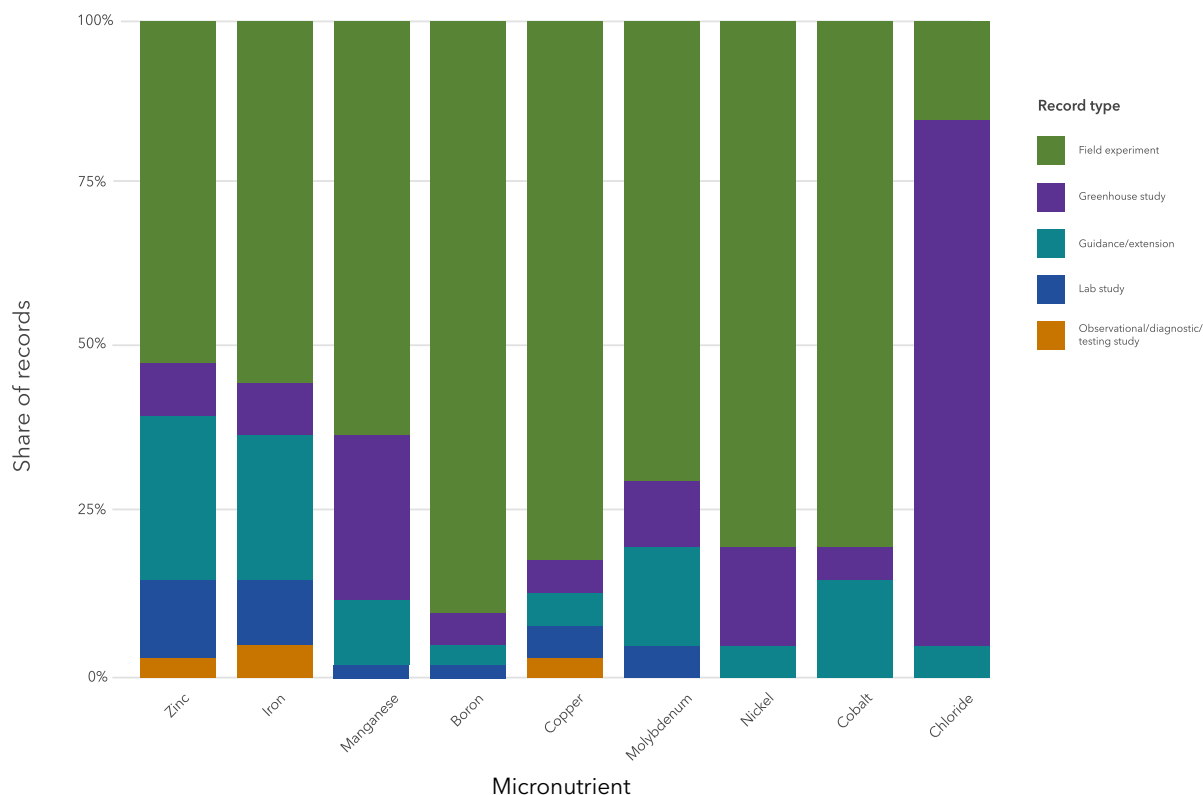


Figure 14. Research approach by micronutrient, Ontario-relevant subset.

Chlorine/chloride, nickel and cobalt were fundamentally different. Their Ontario-relevant knowledge was too sparse to support the same level of characterization. Percentage distributions in Figure 14 can be misleading for these micronutrients because the stacked bars are based on very small numbers of records. For example, cobalt was represented by only two records, so a large percentage of its bar can represent a single record. The principal finding for these micronutrients is therefore scarcity of Ontario-relevant knowledge, rather than the apparent proportional balance among research approaches.

The Ontario-relevant knowledge base consequently does not provide the same foundation for all nine micronutrients. Zinc, iron, manganese, copper and boron are supported by comparatively larger and more diverse bodies of knowledge; molybdenum has a smaller foundation; and chlorine/chloride, nickel and cobalt remain sparsely represented. This unevenness is important for interpreting the remainder of the systematic map. Apparent gaps in management interventions, outcomes, diagnostic information or other areas may reflect not only gaps within the knowledge for a particular micronutrient, but also the limited size of the underlying Ontario-relevant knowledge itself.

Knowledge depth also differed in its coverage of the two target crops (Figure 15). The better-represented micronutrients generally had Ontario-relevant knowledge available for both corn and soybean, particularly zinc, iron and manganese. By contrast, the already limited knowledge for molybdenum, chlorine/chloride, nickel and cobalt remained sparse when

separated by crop. This distinction is important because the total number of records for a micronutrient can obscure differences in the amount of knowledge available to support management in corn versus soybean. Taken together, the micronutrient, research-approach and crop analyses show that Ontario-relevant knowledge is deepest where relatively large numbers of records are accompanied by diverse research approaches and coverage of both crops. For the least-represented micronutrients, limitations therefore extend beyond small record totals to the range of crop-specific management questions that can be examined.

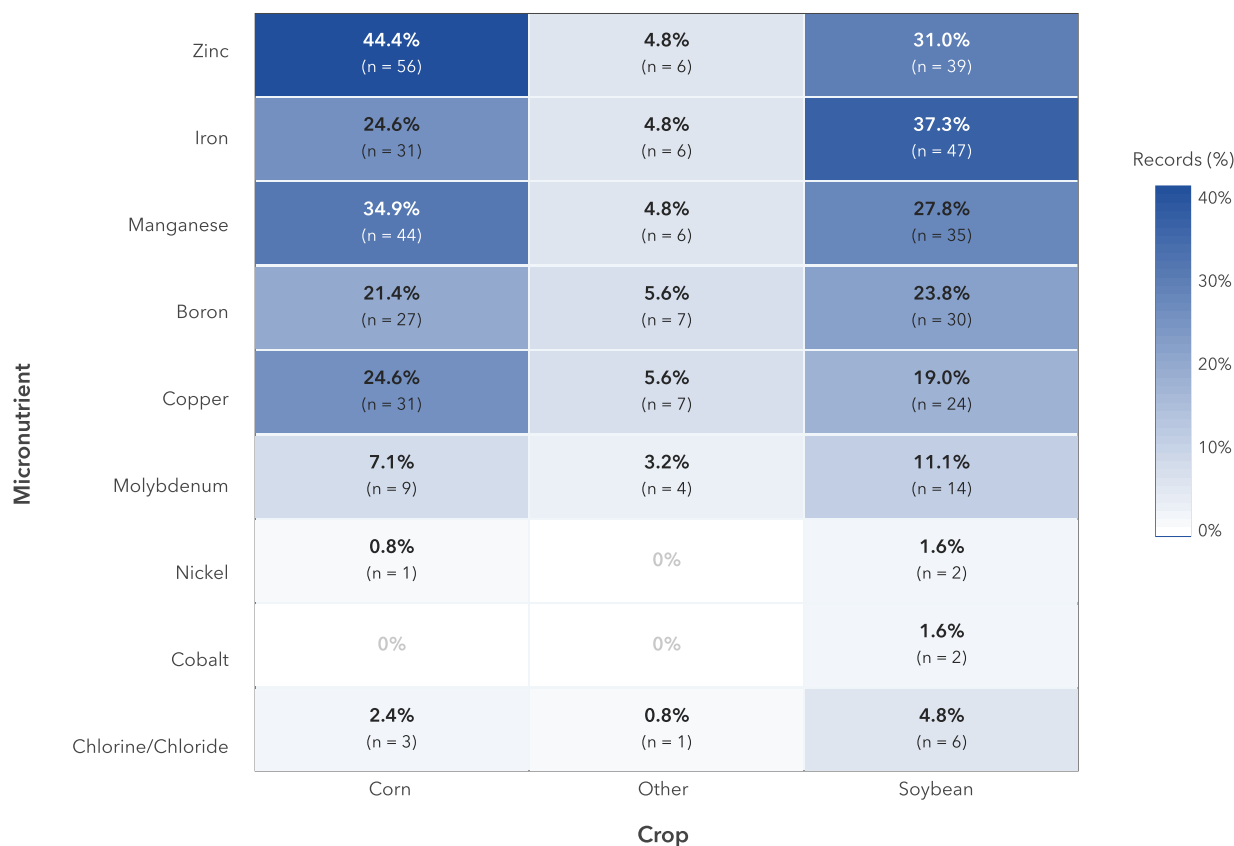


Figure 15. Micronutrient by crop, as a percentage of the Ontario-relevant subset. Zinc, iron and manganese show the strongest representation across both crops; molybdenum, nickel, cobalt and chlorine each appear in fewer than 12% of Ontario-relevant records for either crop, confirming that the limited evidence for these micronutrients persists within the most locally applicable subset of the literature.

Micronutrient management interventions

Ontario-relevant management knowledge includes both information about applying micronutrients and information relevant to determining whether intervention is needed. The Ontario-relevant literature addressed micronutrient management through a range of intervention approaches, with the greatest attention given to soil and foliar applications. Soil application was the most frequently represented intervention, appearing in 34.1% of records (n = 43), followed closely by foliar or leaf application at 31.0% (n = 39). Seed treatments were represented in 12.7% of records (n = 16), while blends and several other intervention

approaches occurred less frequently (Figure 16). The available management knowledge was therefore concentrated around the two principal routes for applying micronutrients to established crops, with a smaller body of information available for seed-based and other approaches.

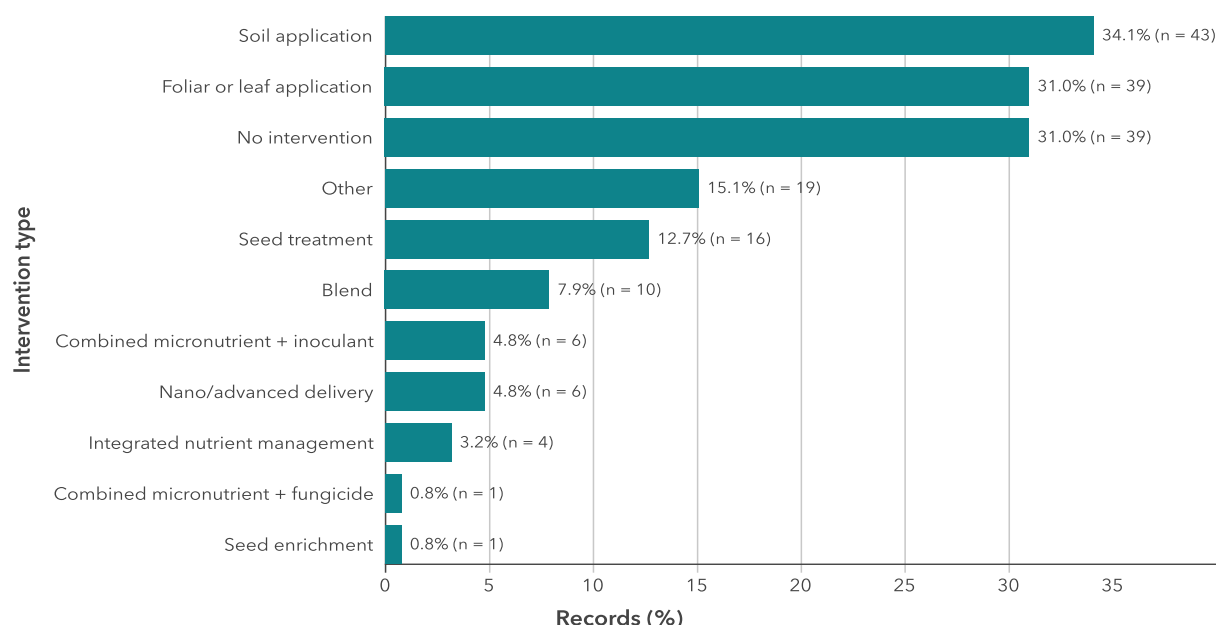


Figure 16. Intervention methods, as a percentage of the Ontario-relevant subset.

Importantly, almost one-third of Ontario-relevant records (31.0%, $n = 39$) involved no micronutrient intervention (Figure 16). This reflects the broader scope of the knowledge relevant to micronutrient management. Not all useful knowledge comes from experiments that apply a micronutrient treatment. Records without an intervention can provide information about micronutrient status, soil or plant concentrations, nutrient availability, diagnosis and other factors that contribute to understanding when and under what conditions micronutrient management may be needed. The Ontario-relevant literature therefore contains both intervention-based knowledge about how micronutrients have been managed and non-intervention knowledge that can contribute to identifying and understanding micronutrient needs.

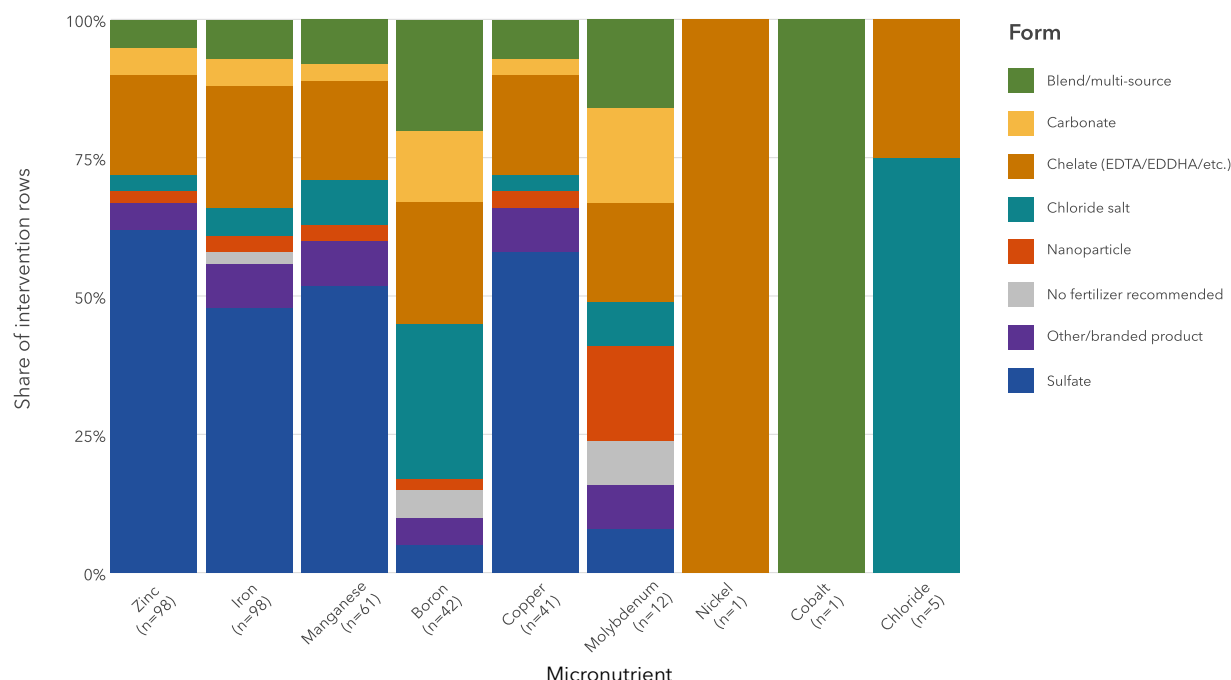


Figure 17. Fertilizer form/source reported, by micronutrient (169 intervention entries)

The frequency with which an intervention appeared in the records should not, however, be interpreted as evidence of its effectiveness. The greater representation of soil and foliar applications shows that these approaches have been investigated more extensively; it does not establish that either approach is more effective or more appropriate for Ontario production than less frequently studied interventions. Evaluating the usefulness of a management practice also requires information about the micronutrient involved, fertilizer source and form, crop, application conditions and measured outcomes. Figure 16 therefore describes the breadth and relative emphasis of management research, rather than the comparative performance of different intervention methods.

The specific fertilizer forms and sources reported in the Ontario-relevant literature add another dimension to this management knowledge. Across the 169 intervention entries extracted from the records, fertilizer form varied both within and among micronutrients (Figure 17). These entries represent individual products or forms rather than individual records because a single record could report more than one intervention, such as separate soil and foliar formulations. The reported entries included sulfates, chelated products, nanoparticle formulations, chloride salts, blended or multi-source products and other formulations; their distribution differed among micronutrients (Figure 17).

A major limitation, however, is that the chemical form of many reported products could not be determined. A substantial share of intervention entries for the more frequently represented micronutrients was classified as an unspecified branded product because the source reported a commercial product name without identifying its underlying chemical form. This limits the ability to compare findings across records or determine whether results

associated with similarly labelled management approaches were generated using comparable fertilizer forms.

The apparent diversity of fertilizer forms also needs to be interpreted in relation to the amount of knowledge available for individual micronutrients. The 169 intervention entries were not evenly distributed among the nine micronutrients, and the very small numbers for some micronutrients do not support broad conclusions about their fertilizer-form profile. Cobalt and nickel, for example, were each represented by only one intervention entry. Moreover, the nickel entry did not represent an experimentally tested fertilizer product; it came from a guidance source indicating that nickel fertilizer was not recommended under the conditions described. Percentage distributions based on these very small numbers should therefore not be interpreted as established management patterns. The Ontario-relevant literature shows considerable diversity in the forms and sources used to deliver micronutrients, but incomplete reporting of chemical form limits the specificity and comparability of that management knowledge.

The intervention analysis shows that Ontario-relevant knowledge covers several approaches to micronutrient management but is concentrated particularly around soil and foliar application. It also shows that the specificity and depth of that management knowledge are uneven. The differences in intervention coverage also reflected the broader differences in knowledge depth identified in the preceding section: micronutrients with very small Ontario-relevant knowledge bases necessarily provided much less information about management approaches and fertilizer forms. Across the records more generally, incomplete reporting of fertilizer form further constrains comparisons among interventions. The systematic map therefore identifies where management practices have received research attention and how they have been implemented, but it does not establish which intervention is most effective or under what Ontario conditions a particular intervention should be recommended.

Outcomes addressed by Ontario-relevant knowledge

The outcomes examined in the Ontario-relevant literature indicate the types of management questions that the knowledge can help address. Some outcomes provide information about crop response to micronutrients, including nutrient uptake, yield, biomass, plant growth and physiological response. Others, particularly soil properties and diagnostic outcomes, contribute to understanding the conditions associated with micronutrient availability and identifying potential micronutrient need. Outcome coverage therefore provides an indication of the breadth of management questions addressed by the Ontario-relevant knowledge, rather than the effectiveness of particular interventions.

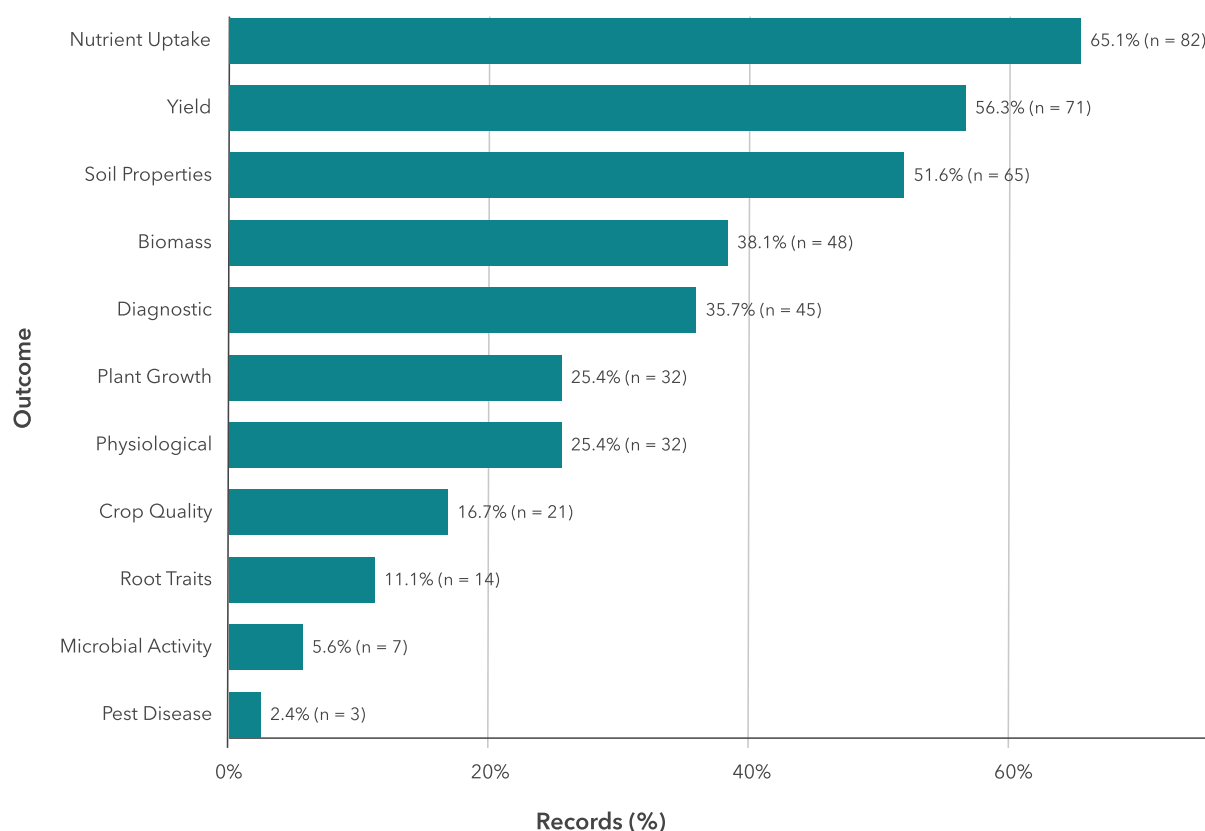


Figure 18. Outcomes assessed, as a percentage of the Ontario-relevant subset.

The Ontario-relevant knowledge addressed several dimensions of micronutrient management (Figure 18). Nutrient uptake was the most frequently reported outcome (65.1%, $n = 82$), followed by yield (56.3%, $n = 71$), soil properties (51.6%, $n = 65$), biomass (38.1%, $n = 48$) and diagnostic outcomes (35.7%, $n = 45$). Together, these outcomes provide information relevant to understanding nutrient acquisition and agronomic response, as well as the soil conditions and diagnostic indicators associated with micronutrient status and potential need. Plant growth, physiological response, crop quality, root traits, microbial activity and pest or disease outcomes were addressed less frequently.

Applying the Ontario-relevance criteria changed the emphasis of this outcome knowledge in important ways. Nutrient uptake and yield remained prominent, but soil-property outcomes increased from 37.1% of the international dataset to 51.6% of the Ontario-relevant subset, while diagnostic outcomes increased from 14.0% to 35.7%. The Ontario-relevant subset has substantially greater representation of knowledge relevant to understanding production conditions and identifying micronutrient status or need. This extends its potential usefulness beyond determining whether crops respond to micronutrients toward understanding the conditions and indicators that may help identify when a micronutrient intervention is warranted. Applied guidance and diagnostic records were also more prominent in the Ontario-relevant subset, although the analysis did not establish whether these patterns were related.

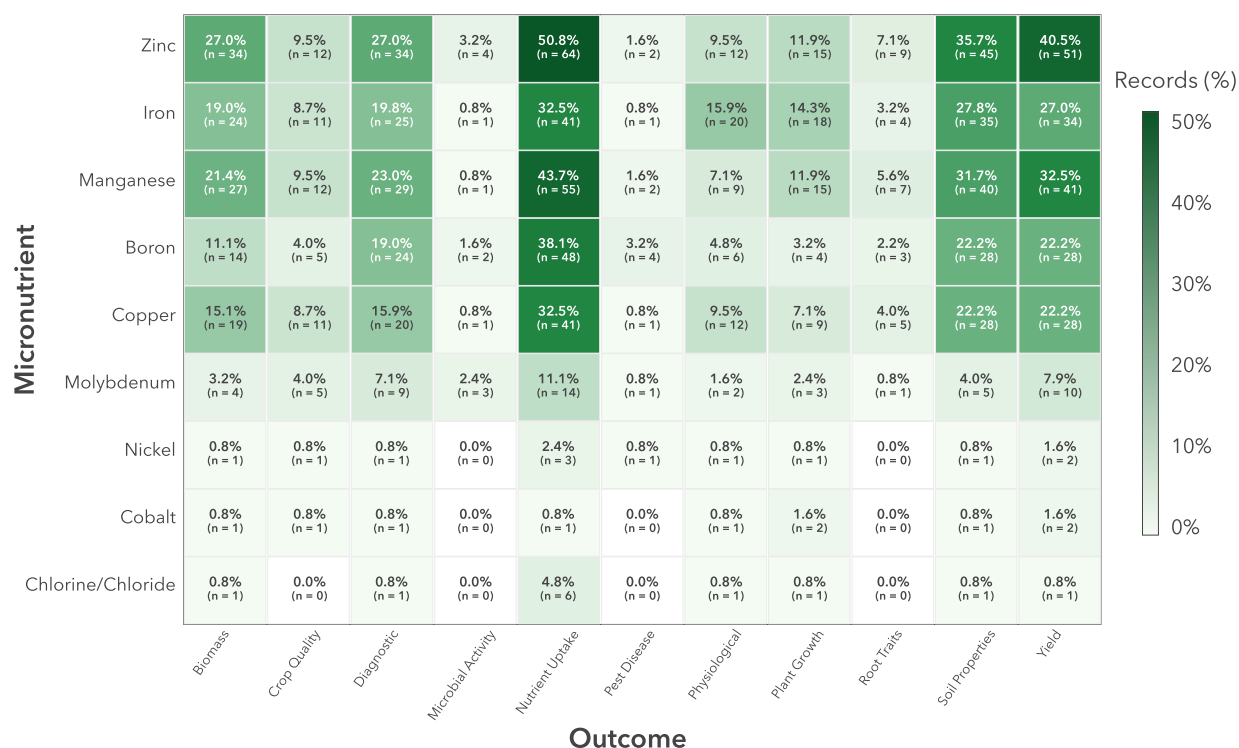


Figure 19. Micronutrient by outcome, as a percentage of the Ontario-relevant subset.

Differences in outcome coverage among micronutrients largely reinforced the knowledge-depth gradient identified earlier (Figure 19). Zinc, iron, manganese, boron and copper were represented across several dimensions of crop response, production context and diagnosis. Molybdenum had a substantially smaller body of outcome information, while the limited underlying knowledge for chlorine/chloride, nickel and cobalt necessarily supported a narrower range of outcomes. Percentage patterns for these sparsely represented micronutrients should therefore be interpreted cautiously because individual records can substantially affect the apparent intensity of the heatmap cells.

Breadth of outcome coverage should also not be interpreted as completeness of knowledge. Representation across several outcome categories indicates that different dimensions of micronutrient management have been investigated, but it does not establish that any of these questions have been adequately resolved. Nor does outcome frequency indicate the effectiveness of an intervention, the methodological quality of the underlying research, or the strength and consistency of crop responses.

Overall, the Ontario-relevant subset provides knowledge relevant to several stages of micronutrient decision-making, from understanding soil conditions and identifying potential micronutrient need to assessing nutrient uptake and agronomic response. However, this capacity is uneven among micronutrients, and considerably less knowledge is available for some dimensions of crop and soil response. Determining whether these findings can inform management under Ontario conditions also depends on knowing the production

environments in which they were generated. The following section therefore examines how completely the Ontario-relevant records characterized the production context.

Characterization of production context

Soil conditions are an important part of the production context for interpreting micronutrient knowledge because they influence nutrient availability and crop response. They are particularly important for the Ontario-relevant subset because most of this knowledge was generated outside Canada. Information about soil type, texture, classification, pH and organic matter can therefore help determine how closely the conditions under which a finding was generated correspond to Ontario production environments. The Ontario-relevant records were examined to determine how these soil characteristics were reported.

Table 10. Records reporting soil characteristics by micronutrient (Ontario-relevant subset, n = 126 records).

Micronutrient	Reported any soil characteristic	Soil type	Texture class	Soil order	Soil pH	Organic matter
Zinc	21	15	7	2	12	3
Iron	20	13	3	3	11	1
Manganese	25	16	9	2	13	3
Boron	17	12	7	2	8	2
Copper	21	15	6	2	11	2
Molybdenum	10	6	2	3	7	1
Nickel	3	1	0	3	3	0
Cobalt	2	1	1	1	1	0
Chlorine	3	2	0	0	2	0

Reporting of soil characteristics varied considerably across the Ontario-relevant knowledge. Among the more extensively represented micronutrients, at least one soil characteristic was reported in 25 manganese records, 21 zinc records, 21 copper records, 20 iron records and 17 boron records. Molybdenum had fewer records reporting soil characteristics (n = 10), while very few records were available for assessing production context for nickel, chlorine/chloride and cobalt (Table 10).

The completeness of the soil information also varied. Soil type descriptions and soil pH were reported more frequently than texture class, soil order or classification, and organic matter. For example, 15 zinc records reported soil type and 12 reported soil pH, compared with seven reporting texture class, two reporting soil order and three reporting organic matter. Similar patterns occurred for iron, manganese, boron and copper. Consequently, the limitation was not only that soil characteristics were inconsistently reported, but also that the

production environment was often only partially characterized when soil information was provided.

Incomplete characterization of production context constrains the transferability of the Ontario-relevant knowledge. The geographic relevance framework identified research and information generated under broad environmental and cropping conditions considered comparable to Ontario, but these criteria cannot establish that individual records represent the soil conditions encountered in particular Ontario production environments. When soil characteristics are incompletely reported, it becomes more difficult to determine how closely a finding corresponds to Ontario conditions or whether differences among findings may be associated with differences in soil environment. This represents a limitation in the contextual information available for interpreting and transferring the knowledge, rather than an assessment of the quality of the underlying research.

The production context is particularly important when interpreting diagnostic information. Soil conditions influence micronutrient availability, but diagnostic interpretation also depends on reference concentrations for crop tissues collected at appropriate growth stages. The next section therefore examines the tissue sufficiency and range intervals reported in the Ontario-relevant literature.

Tissue sufficiency and range intervals

Plant tissue analysis can help assess crop micronutrient status, but its diagnostic value depends on having appropriate reference concentrations for the crop, tissue sampled and stage of crop development. The Ontario-relevant literature was therefore examined for tissue nutrient concentrations reported as adequate, sufficient or within an acceptable range for normal crop growth. These ranges provide potentially useful reference information for interpreting tissue-test results and developing diagnostic guidance (Tables 11–16).

Tables 11–16 list 67 tissue sufficiency or range entries from eight distinct source records, covering six of the nine micronutrients. Zinc had the most entries ($n = 16$), followed by boron ($n = 14$), manganese ($n = 13$), copper ($n = 11$) and iron ($n = 11$). Two entries reported molybdenum ranges; none reported tissue sufficiency ranges for nickel, cobalt or chlorine/chloride. These counts describe the listed ranges, not the number of independent records available for each micronutrient.

The reported ranges also demonstrate why tissue nutrient concentrations cannot be interpreted independently of sampling protocol. Reference values were reported for different plant tissues and developmental stages, including whole young plants during vegetative growth, leaves or trifoliates around flowering or silking, and grain at maturity. Zinc provides a clear example: reported corn ranges differed among whole plants at V5, ear leaves around silking and harvested grain, while soybean ranges similarly varied among young plants, flowering-stage trifoliates and grain (Table 11). These differences do not necessarily indicate disagreement among sources. Rather, they demonstrate that tissue nutrient concentrations have meaning only in relation to a defined crop, tissue and growth stage.

When comparable tissues and growth stages were considered, the degree of consistency differed among micronutrients. Boron (Table 12) and copper (Table 14) showed substantial overlap among several comparable corn and soybean ranges, suggesting some convergence in the available reference information. Manganese ranges were broader (Table 13). Iron showed particularly wide variation: reported corn ear-leaf ranges around silking included 87–448 ppm in one source compared with approximately 20–250 ppm in two others, while soybean flowering-stage leaf or trifoliolate ranges extended from approximately 50–350 ppm to 83–384 ppm (Table 15). These differences indicate that published tissue ranges cannot be assumed to provide equally consistent diagnostic reference information for every micronutrient.

The limitations were more pronounced for the less-represented micronutrients. Only two Ontario-relevant records reported molybdenum tissue ranges, both identifying 1.0–5.0 ppm for soybean trifoliolate tissue around flowering; no comparable corn range was identified (Table 16). Although these two values agree, they provide a very limited foundation for diagnostic interpretation. No comparable tissue sufficiency information was identified for nickel, cobalt or chlorine/chloride. These findings reinforce the broader differences in the depth and availability of Ontario-relevant knowledge identified elsewhere in the systematic map.

The tissue-sufficiency analysis shows that potentially useful diagnostic reference information exists for zinc, boron, manganese, copper and iron in both corn and soybean, but that its consistency varies. Tissue type and crop growth stage are integral to interpretation, and ranges generated using different sampling protocols should not be treated as directly interchangeable. Diagnostic information is much more limited for molybdenum and was not identified for nickel, cobalt or chlorine/chloride.

The existence of a published range does not, on its own, establish that the range is appropriate for Ontario or should be adopted as a provincial diagnostic threshold. Rather, the ranges identified through the systematic map show where potentially useful diagnostic knowledge exists, where comparable sources converge or differ, and where important gaps remain. The following section compares these Ontario-relevant ranges with current Ontario tissue-test guidance to identify areas of alignment, divergence and missing guidance.

Zinc (Zn)

Table 11. Tissue sufficiency/range intervals reported for zinc in corn and soybean, by tissue, growth stage and source record ID.

Crop	Tissue/matrix	Growth stage/condition	Range (ppm)	Record ID
Corn	Base of ear	Initial silk	20-70	724
Corn	Ear leaf	Ear leaf at silking (R1)	14-45	227
Corn	Whole plant	Whole young plant (V5)	20-63	227
Corn	Ear leaf	Silking	20-70	1135
Corn	Ear leaf	Initial silking	20-70	800
Corn	Ear leaf	Tasseling to silk	20-100	724
Corn	Grain	Harvested grain (R6)	10-36	227
Corn	Maize tissue	General maize tissue optimum (cited in introduction)	20-60	429
Corn	Whole tops	Less than 12 in. tall	20-70	724
Soybean	Grain	Harvested grain (R8)	26-50	227
Soybean	Trifoliolate leaves	Early flowering	21-80	724
Soybean	Trifoliolate leaf	R1-R2 before R3	25-60	1023
Soybean	Upper trifoliolate	Upper trifoliolate at flowering (R1)	18-76	227
Soybean	Uppermost full leaves	Prior to or early flowering	20-50	1135
Soybean	Uppermost trifoliolate	Prior to initial flowering	21-50	800
Soybean	Whole young plant	Whole young plant (V5)	17-80	227

Boron (B)

Table 12. Tissue sufficiency/range intervals reported for boron in corn and soybean, by tissue, growth stage and source record ID.

Crop	Tissue/matrix	Growth stage/condition	Range (ppm)	Record ID
Corn	Base of ear	Initial silk	5-25	121
Corn	Ear leaf	Ear leaf at silking (R1)	10-44	227
Corn	Whole plant	Whole young plant (V5)	16-32	227
Corn	Ear leaf	Silking	4-25	1135
Corn	Ear leaf	Initial silking	4-25	800
Corn	Grain	Harvested grain (R6)	3-10	227
Corn	Whole tops	Less than 12 in. tall	5-25	121
Soybean	Grain	Harvested grain (R8)	25-52	227
Soybean	Trifoliate leaves	Early flowering	20-60	121
Soybean	Trifoliate leaf	R1-R2 before R3	25-60	1023
Soybean	Upper trifoliate	Upper trifoliate at flowering (R1)	45-100	227
Soybean	Uppermost full leaves	Prior to or early flowering	25-50	1135
Soybean	Uppermost trifoliate	Prior to initial flowering	21-55	800
Soybean	Whole young plant	Whole young plant (V5)	37-74	227

Manganese (Mn)

Table 13. Tissue sufficiency/range intervals reported for manganese in corn and soybean, by tissue, growth stage and source record ID.

Crop	Tissue/matrix	Growth stage/condition	Range (ppm)	Record ID
Corn	Ear leaf	Ear leaf at silking (R1)	16-86	227
Corn	Whole plant	Whole young plant (V5)	15-111	227
Corn	Ear leaf	Silking	20-150	1135
Corn	Ear leaf	Initial silking	20-150	800
Corn	Grain	Harvested grain (R6)	3-8	227
Corn	Leaves from base of ear	Initial silk	15-150	1160
Soybean	Grain	Harvested grain (R8)	18-42	227
Soybean	Most recently matured trifoliolate leaves	Early flowering	17-100	1160
Soybean	Trifoliolate leaf	R1-R2 before R3	30-100	1023
Soybean	Upper trifoliolate	Upper trifoliolate at flowering (R1)	22-124	227
Soybean	Uppermost full leaves	Prior to or early flowering	21-150	1135
Soybean	Uppermost trifoliolate	Prior to initial flowering	21-100	800
Soybean	Whole young plant	Whole young plant (V5)	24-170	227

Copper (Cu)

Table 14. Tissue sufficiency/range intervals reported for copper in corn and soybean, by tissue, growth stage and source record ID.

Crop	Tissue/matrix	Growth stage/condition	Range (ppm)	Record ID
Corn	Ear leaf	Ear leaf at silking (R1)	6-19	227
Corn	Whole plant	Whole young plant (V5)	3-17	227
Corn	Ear leaf	Silking	6-20	1135
Corn	Ear leaf	Initial silking	6-20	800
Corn	Grain	Harvested grain (R6)	1-4	227
Soybean	Grain	Harvested grain (R8)	11-24	227
Soybean	Trifoliate leaf	R1-R2 before R3	6-20	1023
Soybean	Upper trifoliate	Upper trifoliate at flowering (R1)	6-18	227
Soybean	Uppermost full leaves	Prior to or early flowering	10-30	1135
Soybean	Uppermost trifoliate	Prior to initial flowering	10-30	800
Soybean	Whole young plant	Whole young plant (V5)	3-37	227

Iron (Fe)

Table 15. Tissue sufficiency/range intervals reported for iron in corn and soybean, by tissue, growth stage and source record ID.

Crop	Tissue/matrix	Growth stage/condition	Range (ppm)	Record ID
Corn	Ear leaf	Ear leaf at silking (R1)	87-448	227
Corn	Whole plant	Whole young plant (V5)	109-800	227
Corn	Ear leaf	Silking	20-250	1135
Corn	Ear leaf	Initial silking	21-250	800
Corn	Grain	Harvested grain (R6)	9-49	227
Soybean	Grain	Harvested grain (R8)	49-107	227
Soybean	Trifoliolate leaf	R1-R2 before R3	55-300	1023
Soybean	Upper trifoliolate	Upper trifoliolate at flowering (R1)	83-384	227
Soybean	Uppermost full leaves	Prior to or early flowering	50-350	1135
Soybean	Uppermost trifoliolate	Prior to initial flowering	51-350	800
Soybean	Whole young plant	Whole young plant (V5)	238-2800	227

Molybdenum (Mo)

Table 16. Tissue sufficiency/range intervals reported for molybdenum in corn and soybean, by tissue, growth stage and source record ID.

Crop	Tissue/matrix	Growth stage/condition	Range (ppm)	Record ID
Soybean	Trifoliolate leaves	R1-R2 before R3	1.0-5.0	1023
Soybean	Uppermost trifoliolate	Prior to initial flowering	1.0-5.0	800

Comparison with current Ontario tissue-test guidance

The tissue sufficiency ranges identified in the Ontario-relevant literature provide an opportunity to examine how published diagnostic information compares with current Ontario tissue-test guidance. The ranges identified in the preceding analysis were compared with the critical and maximum normal tissue concentrations published by the Ontario Ministry of Agriculture, Food and Agribusiness (OMAFRA) in the Agronomy Guide for Field Crops, Publication 811 (2022). To make the comparison as appropriate as possible, only literature values for tissues and growth stages that most closely matched the OMAFRA sampling protocols were used (Tables 17 and 18).

Table 17. Comparison of OMAFA critical and maximum normal tissue concentrations for corn with matched systematic map ranges

Micronutrient	OMAF critical (ppm)	OMAF max. normal (ppm)	Systematic-map range, matched stage (ppm) [Record ID]	Assessment
Zn	20.0	70.0	20-63, whole plant V5 [227]; 14-100, ear leaf silking [227,1135,800,724]	Broad consistency ² – OMAFA values fall within the matched literature ranges.
B	2.0	25.0	4-44, ear leaf silking [227,1135,800]	Partial consistency – the maximum normal value aligns with some reported upper bounds; the critical value is below matched lower bounds.
Cu	2.0	20.0	6-20, ear leaf silking [227,1135,800]	Partial consistency – the maximum normal value aligns with reported upper bounds; the critical value is below matched lower bounds.
Mn	15.0	150.0	16-150, ear leaf silking [227,1135,800]	Broad consistency – close agreement at both bounds.
Mo	Not reported	Not reported	No comparable corn Mo tissue range identified in the Ontario-relevant subset	No comparable tissue benchmark was identified in either source. Mo has not been found to be deficient in corn in Ontario.
Fe	Not reported	Not reported	20-448, ear leaf silking [227,1135,800]	No OMAFA reference value; Fe has not been found to be deficient in corn in Ontario.

Table 18. Comparison of OMAFA critical and maximum normal tissue concentrations for soybean with matched systematic map ranges

Micronutrient	OMAF critical (ppm)	OMAF max. normal (ppm)	Systematic-map range, matched stage (ppm) [Record ID]	Assessment
Zn	12.0	80.0	18-80, trifoliolate/upper trifoliolate, first flower-R1 [227,724,1135,800]	Partial consistency – the maximum normal value aligns with the literature upper bound; the critical value is below matched lower bounds.
B	20.0	55.0	20-100, trifoliolate/upper trifoliolate, first flower-R1 [227,121,1135,800]	Broad consistency across most matched records; one source reports a higher upper bound.
Cu	4.0	30.0	6-30, trifoliolate/upper trifoliolate, first flower-R1 [227,1135,800]	Broad consistency – close agreement at both bounds.
Mn	14.0	100.0	17-150, trifoliolate/upper trifoliolate, first flower-R1 [227,1160,1135,800]	Partial consistency – the critical value is below matched lower bounds and some sources report higher upper values.
Mo	0.5	5.0	1.0-5.0, uppermost trifoliolate, pre-flowering [800]	Partial consistency – the maximum normal value aligns; the critical value is below the matched lower bound.
Fe	Not reported	Not reported	50-384, trifoliolate/upper trifoliolate, first flower-R1 [227,1135,800]	No OMAFA reference value; Fe has not been found to be deficient in soybean in Ontario.

Overall, the comparison identified three relationships between current Ontario guidance and the Ontario-relevant literature: areas of broad alignment, areas of divergence, and gaps where reference values were absent. Several OMAFA reference values showed substantial numerical correspondence with ranges reported in the Ontario-relevant literature. For corn, the OMAFA zinc range fell within the matched literature values, while manganese showed close agreement at both the lower and upper bounds. The maximum normal concentrations for boron and copper also corresponded closely with reported upper bounds. For soybean, copper showed close agreement, boron was broadly consistent across most matched records, and the maximum normal concentration for zinc corresponded with the literature upper bound. These areas of convergence indicate that several current Ontario reference values are broadly consistent with tissue concentrations reported in literature generated under conditions considered relevant to Ontario.

Where differences occurred, they were particularly apparent at the lower end of the reference ranges. OMAFA critical concentrations for corn boron and copper were below the lower bounds of the matched literature ranges. For soybean, the critical concentrations for zinc,

manganese and molybdenum were also below the matched lower bounds. At the upper end, soybean manganese was a notable exception to the general pattern of agreement: OMAFA reports a maximum normal concentration of 100 ppm, while matched literature ranges extended to 150 ppm. These differences identify specific areas where current Ontario reference values and the Ontario-relevant literature do not fully align.

These differences should not be interpreted as demonstrating that the OMAFA reference values are incorrect. A critical concentration and the lower bound of a published sufficiency range are not necessarily equivalent diagnostic measures, and the systematic map did not examine how individual thresholds were derived. Nor did it assess the quality of the underlying research or validate the ability of individual values to distinguish micronutrient deficiency from sufficiency or predict crop response under Ontario conditions. The observed differences therefore identify diagnostic questions for further investigation rather than evidence that particular Ontario thresholds should be changed.

The comparison also identified gaps in current Ontario guidance, but these gaps were not all alike. Iron provides the clearest example of potentially relevant diagnostic information being available despite the absence of an Ontario reference value. OMAFA does not report critical or maximum normal tissue concentrations for iron in either corn or soybean, while matched Ontario-relevant ranges were identified for both crops. Corn ear-leaf values around silking ranged from 20 to 448 ppm, while soybean trifoliolate values around first flowering ranged from 50 to 384 ppm. The breadth of these ranges demonstrates why the existence of published values is not sufficient to establish an Ontario threshold, but it identifies iron as an area where relevant diagnostic information is available for more focused evaluation.

Molybdenum illustrates a different type of gap. For soybean, OMAFA reports a critical concentration of 0.5 ppm and a maximum normal concentration of 5.0 ppm, compared with a matched literature range of 1.0–5.0 ppm. For corn, however, neither OMAFA nor the Ontario-relevant literature provided a comparable tissue benchmark. The absence of an Ontario reference value therefore does not necessarily mean that relevant published information is available to address the gap. For iron, the map identified potentially useful literature that could be examined further; for corn molybdenum, it identified a more fundamental gap in the available diagnostic knowledge.

The comparison shows that several current Ontario tissue reference values broadly align with Ontario-relevant published ranges, while also identifying specific areas of divergence and missing guidance. These findings demonstrate the value of the systematic map for identifying where existing Ontario reference values numerically align with published ranges for approximately matched tissues and growth stages, where differences warrant further examination, and where diagnostic knowledge remains limited. The systematic map does not establish new tissue-test thresholds or determine whether existing Ontario values should be revised. Such decisions would require a focused assessment of the underlying research, including the conditions under which reference values were developed and their ability to

distinguish micronutrient sufficiency from deficiency or predict crop response under Ontario conditions.

Conclusions and research priorities

A large international literature does not necessarily provide knowledge applicable to Ontario.

The systematic map identified a substantial and growing international literature of 1,365 records on micronutrients in corn and soybean production. However, only 126 records (9.2%) met the criteria for high or moderate Ontario relevance. The important conclusion is not simply that the Ontario-relevant subset was much smaller than the full dataset. Rather, the quantity of international research on a topic should not be confused with the amount of knowledge identified as having greater potential to inform Ontario production conditions. A large literature generated under substantially different soil, climate and production conditions does not, on its own, provide a correspondingly large body of knowledge applicable to Ontario.

At the same time, Ontario-relevant knowledge was not limited to research conducted within the province or elsewhere in Canada. Comparable production regions in the United States and northern and central Europe provided a much larger pool of potentially transferable knowledge. The geographic tier framework therefore expanded the knowledge available to inform Ontario management while providing a systematic basis for considering its transferability. Classification as Ontario relevant indicates greater potential for transfer, however, rather than demonstrating that individual findings are directly applicable under Ontario conditions.

Ontario-relevant knowledge is uneven across micronutrients and management questions

The amount and composition of available knowledge differed substantially among the nine micronutrients. Zinc, iron and manganese had the largest Ontario-relevant bodies of knowledge, with boron and copper also comparatively well represented. Molybdenum had a smaller body of knowledge, while chlorine/chloride, nickel and cobalt were represented by very few records. These differences largely reflected the international knowledge landscape and indicate that applying the Ontario-relevance criteria did not fundamentally rebalance the distribution of micronutrient knowledge.

Differences were also evident in the types of information available. The Ontario-relevant subset retained a substantial experimental component while containing a much larger relative contribution from guidance, extension and diagnostic information than the international literature. For the more extensively represented micronutrients, knowledge was distributed across multiple research approaches, interventions and outcomes. The less-represented micronutrients generally provided a narrower foundation for examining management questions. These patterns describe differences in the volume, breadth and

composition of available knowledge; they do not establish differences in evidence quality, consistency or effectiveness.

Importantly, a knowledge gap can arise for different reasons. In some cases, relatively little Ontario-relevant knowledge exists for a micronutrient. In others, a substantial body of literature exists but does not provide the particular information needed for a management decision. These are different problems and require different responses. The first may warrant additional research if the micronutrient represents an important Ontario management need; the second may require more targeted research, validation or synthesis of existing information rather than simply additional studies of the same kind.

The most consequential gaps concern information needed to support management decisions

Across the Ontario-relevant analyses, several limitations affected the potential usefulness of the available knowledge for management and recommendation development. Information describing soil and production context was uneven in type and extent, limiting the ability to determine how closely the conditions represented in individual records correspond to particular Ontario production environments. Management information also varied in specificity. Soil and foliar applications were the most extensively represented intervention approaches, but fertilizer form was not always clearly reported, particularly where sources identified commercial products without specifying their chemical composition.

Diagnostic information presents a more complex picture. Potentially useful tissue sufficiency information was identified for zinc, boron, manganese, copper and iron in both corn and soybean, although the degree of consistency among published ranges varied and interpretation depended on tissue type and crop growth stage. Comparable information was much more limited for molybdenum and was not identified for nickel, cobalt or chlorine/chloride.

Comparison with current OMAFA tissue-test guidance further demonstrated that diagnostic knowledge gaps are not all alike. Several existing Ontario reference values broadly aligned with ranges reported in the Ontario-relevant literature, while specific areas of divergence were also identified. Iron represented a different type of gap: OMAFA provides no tissue reference value for either corn or soybean, although potentially relevant published ranges were identified for both crops. Corn molybdenum represented a more fundamental information gap because neither current Ontario guidance nor the Ontario-relevant literature provided a comparable tissue benchmark. These findings identify specific questions for further assessment; they do not establish that existing Ontario thresholds are incorrect or that published ranges should be adopted as new provincial thresholds.

Economic information was another persistent limitation. Economic analysis was uncommon in both the international literature and the Ontario-relevant subset, occurring in only 6.9% and 4.8% of records, respectively. This limits the ability of the mapped literature to address an important practical question: not simply whether a micronutrient intervention can affect crop

response or yield, but whether the response is sufficient to justify the cost of intervention under relevant production conditions.

Research priorities should be targeted to specific decision needs

Not every gap identified through the systematic map warrants new research. Decisions about research priorities should also consider the agronomic importance of the micronutrient, likelihood of deficiency or crop response under Ontario conditions, relevance to specific management decisions, consequences of remaining uncertain, and whether existing information may already be sufficient to support current recommendations. Based on the findings of the map, six areas warrant particular consideration:

Ontario and closely comparable field validation. Additional field research would be most valuable where transferability remains an important source of uncertainty and the management question has demonstrated relevance to Ontario corn or soybean production.

Targeted investigation of poorly represented micronutrients. Molybdenum, nickel, cobalt and chlorine/chloride warrant further investigation where a plausible Ontario agronomic or diagnostic need can be established. Their small mapped knowledge bases should not, by themselves, be interpreted as justification for equivalent research investment in all four micronutrients.

Diagnostic validation and focused review of current guidance. Research and synthesis should concentrate on the specific gaps and divergences identified by the map, including the absence of OMAFA iron tissue reference values, the divergence in the upper reference value for manganese in soybean, and the lack of a comparable corn molybdenum benchmark, rather than undertaking an undifferentiated reassessment of all current tissue thresholds.

Better characterization of production context and management interventions. Future research and guidance should report soil and production conditions and provide sufficient detail about fertilizer form, source, rate, timing and application method to support comparison among findings and assessment of their transferability to Ontario conditions.

Greater attention to management-relevant outcomes. Diagnostic indicators and economic performance warrant particular attention alongside established measures such as nutrient uptake and yield. Economic analysis is especially important for determining whether observed agronomic responses translate into practical value for growers.

Focused synthesis before commissioning new research. Where relevant information already exists but has not been adequately evaluated for Ontario application, focused synthesis and validation may be more appropriate than generating additional primary research. Iron tissue diagnostics provide a clear example, whereas the absence of a comparable corn molybdenum benchmark points toward a more fundamental knowledge gap.

The systematic map therefore does not support a general conclusion that Ontario needs more micronutrient research across all nine micronutrients. Instead, it identifies a more specific need for better-targeted knowledge development. The map identifies particular micronutrients, diagnostic and management questions, transferability limitations, and gaps in

current guidance as candidate priorities; their relative value depends on whether resolving the uncertainty would materially improve Ontario corn and soybean management. In some areas this will require new field research; in others, validation, focused synthesis or improved reporting of existing research may provide the more appropriate response.

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Supplemental Information

Supplemental Table S1. Crop type, as a percentage and count of the full dataset (n = 1,365). Related discussion: Distribution of knowledge among micronutrients and crops

Crop type	Records	% of full dataset
Corn only	614	44.9%
Soybean only	549	40.2%
Corn + other crops	92	6.7%
Soybean + other crops	43	3.2%
Corn + soybean	67	4.9%

Supplemental Table S2. Organizations included in the grey literature searches.

Organization	URL
Provincial & Federal government agricultural ministries in Canada	
Ontario Ministry of Agriculture	https://www.ontario.ca/page/ministry-agriculture-food-and-agribusiness
Alberta Ministry of Agriculture	https://www.alberta.ca/agriculture
Manitoba Ministry of Agriculture	https://www.gov.mb.ca/agriculture/
Saskatchewan Ministry of Agriculture	https://www.saskatchewan.ca/government/government-structure/ministries/agriculture
PEI ministry of Agriculture	https://www.princeedwardisland.ca/en/topic/agriculture
BC ministry of Agriculture	https://www2.gov.bc.ca/gov/content/governments/organizational-structure/ministries-organizations/ministries/agriculture
New Brunswick Ministry of Agriculture	https://www2.gnb.ca/content/gnb/en/departments/10/agriculture.html
Newfoundland and Labrador Ministry of Agriculture	https://www.gov.nl.ca/ffa/
Nova Scotia Ministry of Agriculture	https://beta.novascotia.ca/government/agriculture
Quebec Ministry of Agriculture	https://www.quebec.ca/gouvernement/ministeres-organismes/agriculture-pecherie-alimentation
Agriculture and Agri-Food Canada (AAFC)	https://agriculture.canada.ca/en
National and Provincial Grains and Oilseeds Commodity Organizations	
Alberta Grains	https://www.albertagrains.com
Alberta Pulse Growers Commission	https://albertapulse.com/
BC Grain Producers Association	https://bcgrain.com
Canada Grains Council (CGC)	https://www.canadagrainscouncil.ca/
Ecological Farmers Association of Ontario	https://efao.ca/
Grain Farmers of Ontario	https://gfo.ca/
Grain Growers of Canada (GGC)	https://graingrowersofcanada.ca/
Manitoba Crop Alliance	https://mbcropalliance.ca/
Manitoba Pulse & Soybean Growers	https://www.manitobapulse.ca/
Perennia Food and Agriculture Corporation	https://www.perennia.ca/

Organization	URL
National and Provincial Grains and Oilseeds Commodity Organizations	
Producteurs de grains du Québec (PGQ)	https://pgq.ca/
Pulse Canada	https://pulsecanada.com/
Saskatchewan Pulse Growers	https://saskpulse.com/
Soy Canada	https://soycanada.ca/
Western Grains Research Foundation (WGRF)	https://wgrf.ca/
Industry Associations	
Fertilizer Canada	https://fertilizercanada.ca/
Fertilizer and Supplements Advisory Committee	https://fsacommittee.ca/
International Agrifood Organizations	
Food and Agriculture Organization (FAO) of the United Nations	https://www.fao.org/home/en
CGIAR (Consultative Group on International Agricultural Research) - including affiliated research centres such as International Maize and Wheat Improvement Center	https://www.cgiar.org/
USDA Agricultural Research Service & Cooperative State Extension Programs	
Alabama	aces.edu
Alaska	uaf.edu/ces
Arizona	extension.arizona.edu
Arkansas	uaex.uada.edu
California	ucanr.edu
Colorado	extension.colostate.edu
Connecticut	extension.uconn.edu
Delaware	udel.edu/extension
Florida	sfyl.ifas.ufl.edu
Georgia	extension.uga.edu

Organization	URL
Hawaii	ctahr.hawaii.edu/site/Extension.aspx
Idaho	uidaho.edu/extension
Illinois	extension.illinois.edu
Iowa	extension.iastate.edu
Kansas	ksre.k-state.edu
Kentucky	extension.ca.uky.edu
Louisiana	lsuagcenter.com
Maine	extension.umaine.edu
Maryland	extension.umd.edu
Massachusetts	ag.umass.edu/extension
Michigan	canr.msu.edu/outreach
Minnesota	extension.umn.edu
Mississippi	extension.msstate.edu
Missouri	extension.missouri.edu
Montana	msuextension.org
Nebraska	extension.unl.edu
Nevada	extension.unr.edu
New Hampshire	extension.unh.edu
New Jersey	njaes.rutgers.edu
New Mexico	extension.nmsu.edu
New York	cce.cornell.edu
North Carolina	ces.ncsu.edu
North Dakota	ndsu.edu/agriculture/extension
Ohio	extension.osu.edu
Oklahoma	extension.okstate.edu
Oregon	extension.oregonstate.edu
Pennsylvania	extension.psu.edu
Rhode Island	web.uri.edu/coopext

Organization	URL
USDA Agricultural Research Service & Cooperative State Extension Programs (Cont'd)	
South Carolina	clemson.edu/extension
South Dakota	extension.sdstate.edu
Tennessee	utextension.tennessee.edu
Texas	agrilifeextension.tamu.edu
Utah	extension.usu.edu
Vermont	uvm.edu/extension
Virginia	ext.vt.edu
Washington	extension.wsu.edu
West Virginia	extension.wvu.edu
Wisconsin	extension.wisc.edu
Wyoming	uwyo.edu/uwe
Fertilizer Manufacturers	
Active AgriScience	https://activeagriscience.com/product/active-copper/
Agrico Canada L.P.	https://www.agricocanada.com/micronutrients/
BRANDT	https://fertilizercanada.ca/membership/member-directory/brandt/
Federated Cooperatives Limited (Coop Agro)	https://www.ourcoop.com/agronomy/crop-nutrients
GROWMARK Inc.	https://www.midwestcoop.ca/Agronomy/Crop-Nutrients
J.R. Simplot Company	https://www.simplot.com/
Lucent Bio	https://fertilizercanada.ca/membership/member-directory/lucient-bio/
Nachurs Alpine Solutions (ALPINE)	https://fertilizercanada.ca/membership/member-directory/alpine/
NexusBioAg	https://fertilizercanada.ca/membership/member-directory/nexusbioag/
Rack Petroleum	https://fertilizercanada.ca/membership/member-directory/rack-petroleum/
TerraLink Horticulture Inc.	https://fertilizercanada.ca/membership/member-directory/terralink-horticulture-inc/

Organization	URL
Fertilizer Manufacturers (cont'd)	
The Mosaic Company	https://www.croptonutrition.com/crop-nutrition/aspire/
Yara Canada Inc.	https://www.yaracanada.ca/crop-nutrition/micronutrient-fertilizers/
Yara Belle Plaine	https://fertilizercanada.ca/membership/member-directory/yara-belle-plaine/
OMEX Agriculture	https://omexcanada.com/crop-nutrients/micro/
Corteva Agriscience	https://www.corteva.com/
Syngenta	https://www.syngenta.com/
Bayer	https://www.bayer.com/en/

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