

# Using evidence to support micronutrient management practices and recommendations in Ontario corn and soybean production

A KNOWLEDGE SYNTHESIS

OCTOBER 2026



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VISTA Science & Technology

October 2026

## Executive Summary

Micronutrient management decisions are complex, creating a need for evidence-informed management practices and recommendations that reflect both the available science and the conditions under which that evidence applies. Making those decisions requires understanding whether there is credible evidence of a micronutrient deficiency, the soil and production conditions contributing to it, the management options available, how the crop responds, whether that response produces a meaningful benefit, and whether the supporting evidence is sufficiently relevant and consistent to guide action.

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 more accessible and useful.

The project produced three complementary reports. The systematic map identifies and characterizes the available literature and its relevance to Ontario production conditions. This knowledge synthesis interprets and integrates the Ontario-relevant knowledge to examine what it collectively tells us about micronutrient management and how different forms of knowledge fit together to support decisions. The Research and Innovation Roadmap draws on the systematic map and knowledge synthesis to identify opportunities to strengthen the evidence available for future micronutrient management, recommendations and decision-making.

The systematic map identified 1,365 records addressing nine micronutrients (boron, chlorine/chloride, cobalt, copper, iron, manganese, molybdenum, nickel and zinc) in corn and soybean production. A geographic tier framework identified 126 records with high or moderate Ontario relevance for deeper extraction and synthesis. These records included peer-reviewed research as well as extension and advisory guidance, handbooks, factsheets and diagnostic information.

A structured, researcher-directed thematic synthesis, supported by generative artificial intelligence, organized the 126 records into six decision pathway components, six knowledge clusters, 26 themes and 76 knowledge concepts. The resulting knowledge architecture is structured as an applied decision pathway with six components that moves from identifying whether intervention may be warranted through understanding response conditions, selecting management options, examining biological response and meaningful outcomes, and interpreting the evidence for recommendations and decisions. The pathway is not a fixed or prescriptive sequence: the components are interconnected and information from one component can change how another is interpreted.

### The knowledge is substantial, but uneven

The Ontario-relevant knowledge is concentrated around crop response, management and plant processes. Agronomic Productivity and Crop Growth was the most extensively represented theme, occurring in 102 of 126 records, followed by Response Direction,

Consistency, and Risk (63 records), Nutrient Physiology, Uptake, and Partitioning (62 records), and Application Route and Placement (61 records). Considerably less information addressed economic performance (5 records), field-specific decision support (9 records), root and rhizosphere processes (9 records), microbial interactions (9 records), and evidence gaps and transferability (7 records). This creates an important imbalance in the Ontario-relevant knowledge base: records addressing crop response are much more numerous than records addressing economic value, field-specific decisions and transferability.

The extent of thematic coverage also differs markedly among micronutrients. Zinc has the broadest coverage across the decision pathway, with iron and manganese also represented across many themes. Boron and copper have substantial but less extensive coverage. Molybdenum has less thematic coverage, while chlorine/chloride, nickel and cobalt are sparsely represented. These differences mean that conclusions supported for one micronutrient cannot automatically be extended to another.

### **Micronutrient response is conditional rather than universal**

Across the synthesis, one of the clearest findings is that micronutrient status and fertilizer responsiveness are not equivalent. Soil and plant analyses, critical levels, sufficiency ranges and deficiency symptoms can contribute to diagnosis, but no single indicator consistently establishes that intervention will produce an agronomic benefit. Diagnostic information is most useful when multiple indicators are interpreted together and within the soil, crop, environmental and management conditions of the field.

The same conditionality applies to management. The knowledge does not identify a single application route, product or management strategy that is consistently superior. Response can depend on nutrient availability, soil pH and carbonate conditions, moisture, temperature, nutrient interactions, crop and genotype, management practices, application method and other production conditions. Management should therefore follow diagnosis: the intervention needs to address a demonstrated micronutrient deficiency and be appropriate to the conditions in which the deficiency occurs.

### **Crop response does not automatically translate into agronomic or economic value**

The synthesis distinguishes among nutrient uptake, tissue concentration, physiological response, root development, biomass, grain yield, grain mineral composition and other outcomes. These responses are related but are not interchangeable. An increase in tissue nutrient concentration demonstrates that nutrient status changed; it does not establish that yield increased. Similarly, improvements in early growth or biomass do not necessarily persist to harvest. The outcome used to judge success must therefore reflect the objective of the intervention.

Economic performance is particularly underdeveloped. Only five records were assigned to the theme: Economic Performance and Profitability. Those records were limited to soybean.

Consequently, one of the most important gaps occurs at the point where agronomic response must be translated into a farm-level decision: whether a response is sufficiently large, consistent and valuable to justify the cost of intervention.

## Better decisions require different forms of knowledge to be connected

Connectivity analyses showed that themes from the six knowledge clusters were frequently addressed within the same records. Themes concerning outcomes often co-occurred with themes concerning biological processes, management, and conditions affecting nutrient availability and response. Diagnostic and management themes also co-occurred with themes concerning evidence interpretation. These analyses describe how topics are represented together in the knowledge base.

Considered alongside the substantive findings of the synthesis, these patterns inform an integrated and potentially iterative decision framework rather than a simple linear pathway. Diagnosis establishes whether there is credible evidence of a problem; causal context helps determine whether response is plausible; management determines how intervention is implemented; biological processes help explain response; outcomes establish whether something of value resulted; and interpretation determines how confidently the findings can be applied. Confidence increases when these different lines of information reinforce one another and should remain lower where important connections are missing.

## Implications for Ontario

The synthesis does not support either routine micronutrient supplementation or the conclusion that micronutrient intervention is generally unnecessary. Both would oversimplify a body of knowledge characterized by conditional and variable responses. Instead, it supports a more targeted approach in which confidence in an intervention increases when there is credible evidence of a micronutrient deficiency; field conditions provide a plausible explanation for it; management is appropriate to the diagnosed deficiency; the expected biological response is plausible; an outcome relevant to the management objective is demonstrated; and the supporting information is sufficiently relevant, consistent and transferable to Ontario production conditions.

For Ontario recommendations and guidance, replicated field information generated in Ontario or under sufficiently comparable production conditions provides the most directly applicable basis for decisions. Mechanistic and controlled-environment research remains valuable for explaining processes and identifying potentially important relationships, but it does not necessarily establish that a treatment will produce a useful field response. Similarly, diagnostic thresholds, rates and recommendations developed elsewhere require consideration of differences in soils, climate, cropping systems, analytical methods and management conditions before being transferred to Ontario.

Future work would be most useful where it strengthens the connections currently limiting evidence-based decisions rather than simply increasing the volume of micronutrient research.

Priorities include stronger local calibration of diagnostic indicators, replicated multi-site field evaluations, clearer comparisons among products and application strategies, economic assessment, longer-term soil and environmental outcomes, and better identification of the conditions that distinguish responsive from non-responsive fields.

The principal contribution of the knowledge synthesis is therefore not a new set of general micronutrient recommendations. It provides a framework for asking better questions before intervention: Is there a credible problem? What is causing it? What intervention fits those conditions? How should the crop respond? Did the response produce something of value? And is the supporting information sufficiently strong and relevant to justify the decision? Used in this way, the systematic map and knowledge synthesis provide a foundation for more targeted extension guidance, more transparent interpretation of micronutrient information and more strategic development of Ontario-specific knowledge.

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# Using evidence to make better micronutrient decisions

Micronutrient management decisions are complex, creating a need for evidence-informed management practices and recommendations that reflect both the available science and the conditions under which that evidence applies. A production decision may depend on whether there is credible evidence of a micronutrient deficiency; what soil, environmental or management conditions may be contributing to it; what management options are available; how the crop responds; whether that response produces a meaningful benefit; and whether the supporting information is sufficiently relevant and consistent to inform a decision.

The project *Scientific evidence to support micronutrient management practices and recommendations for corn and soybean production 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. *Mapping the evidence to support micronutrient management practices and recommendations in Ontario corn and soybean production – A Systematic Map* identified and characterized 1,365 records published from 2010–2025 and identified 126 records generated under conditions considered to have high or moderate relevance to Ontario. It provides the evidence foundation for the broader project. Covering nine micronutrients (boron, chlorine/chloride, cobalt, copper, iron, manganese, molybdenum, nickel and zinc), it established 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. *Strengthening the evidence for micronutrient management in Ontario corn and soybean production: A Research and Innovation Roadmap* draws on the findings of the knowledge synthesis and the systematic map to identify opportunities to strengthen the evidence available for future micronutrient management, recommendations and decision-making.

This 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. The purpose of the knowledge synthesis is therefore not to produce a new set of generalized micronutrient recommendations. It organizes and interprets the available Ontario-relevant knowledge so that production, extension, advisory, research and policy decisions can be made with a clearer understanding of what is known, how different types of information relate to one another, where conclusions remain conditional or uncertain, and where additional knowledge would be most useful.

## Generative artificial intelligence use

Generative artificial intelligence was used in the analytical synthesis as described in *Developing the knowledge architecture* (p. 4) 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.

## From systematic map to knowledge synthesis

The systematic map identified 1,365 records published from 2010–2025 addressing nine micronutrients in corn and soybean production and characterized their distribution across micronutrients, crops, geographic regions, research approaches, management interventions and outcomes. A geographic tier framework was then used to identify records generated under environmental and production conditions considered sufficiently comparable to Ontario. The 126 records rated as having high or moderate Ontario relevance underwent deeper extraction and form the knowledge base for this synthesis.

The 126 records include peer-reviewed original research as well as extension and advisory guidance, handbooks, factsheets, diagnostic information and tissue-testing material. The term record is therefore used for individual sources rather than treating all of the available information as research studies.

The systematic map established the extent, distribution and characteristics of this knowledge base. The synthesis moves from characterization to interpretation and integration: it identifies the major micronutrient management decisions addressed by the Ontario-relevant knowledge, organizes the information needed to make those decisions, and examines how different forms of knowledge combine to support or limit those decisions. The resulting knowledge architecture and applied decision pathway are introduced in the following section.

## From the knowledge architecture to an applied pathway

The synthesis organized the 126 Ontario-relevant records into six decision pathway components. Each component has a corresponding knowledge cluster; together, the clusters contain 26 themes and 76 knowledge concepts (Figures 1A and 1B). The components address the information needed to establish whether intervention may be warranted, understand conditions affecting response, select management, evaluate crop responses and outcomes, and interpret the knowledge for decisions:

1. Establishing whether micronutrient intervention is warranted
2. Understanding what influences micronutrient availability and crop response

3. Selecting an appropriate micronutrient management strategy
4. Understanding how crops respond to micronutrients
5. Determining whether micronutrient intervention produces meaningful benefits
6. Translating the knowledge into recommendations and decisions

The components are presented from diagnosis through evidence interpretation, but they are not a rigid sequence or decision algorithm. Diagnosis, production context, management, biological response, outcomes and interpretation are interconnected; information from one component can change how another is understood.

Figure 1A presents the six decision pathway components, the six corresponding knowledge clusters and 26 themes. Figure 1B provides the complete knowledge architecture, including the 76 underlying knowledge concepts. The architecture therefore serves two purposes: it provides an analytical framework for organizing the Ontario-relevant knowledge and an applied framework for examining how different types of information contribute to micronutrient decisions.

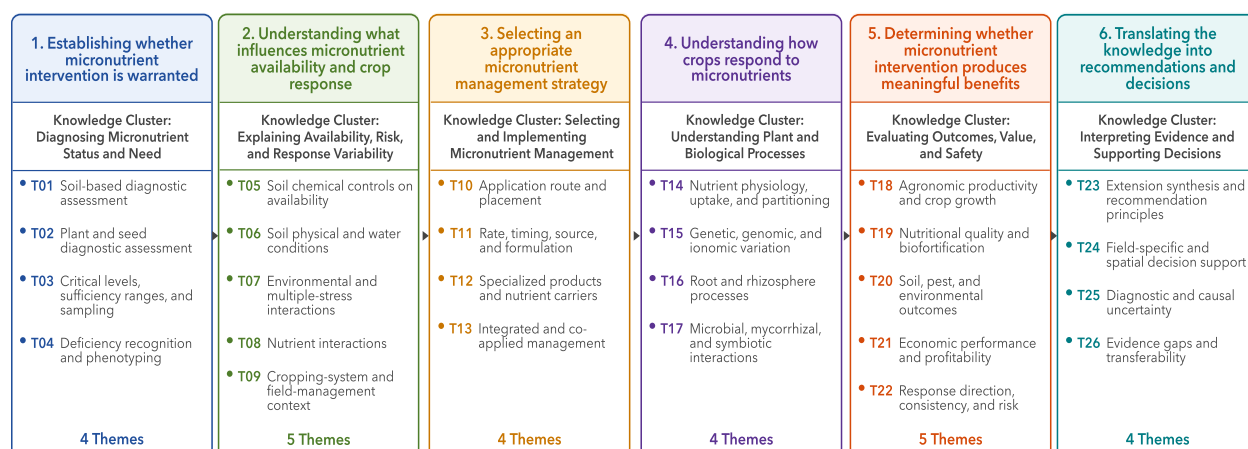


Figure 1A. Simplified knowledge architecture showing the six decision pathway components, their corresponding knowledge clusters, and the 26 themes used to organize the micronutrient knowledge synthesis.

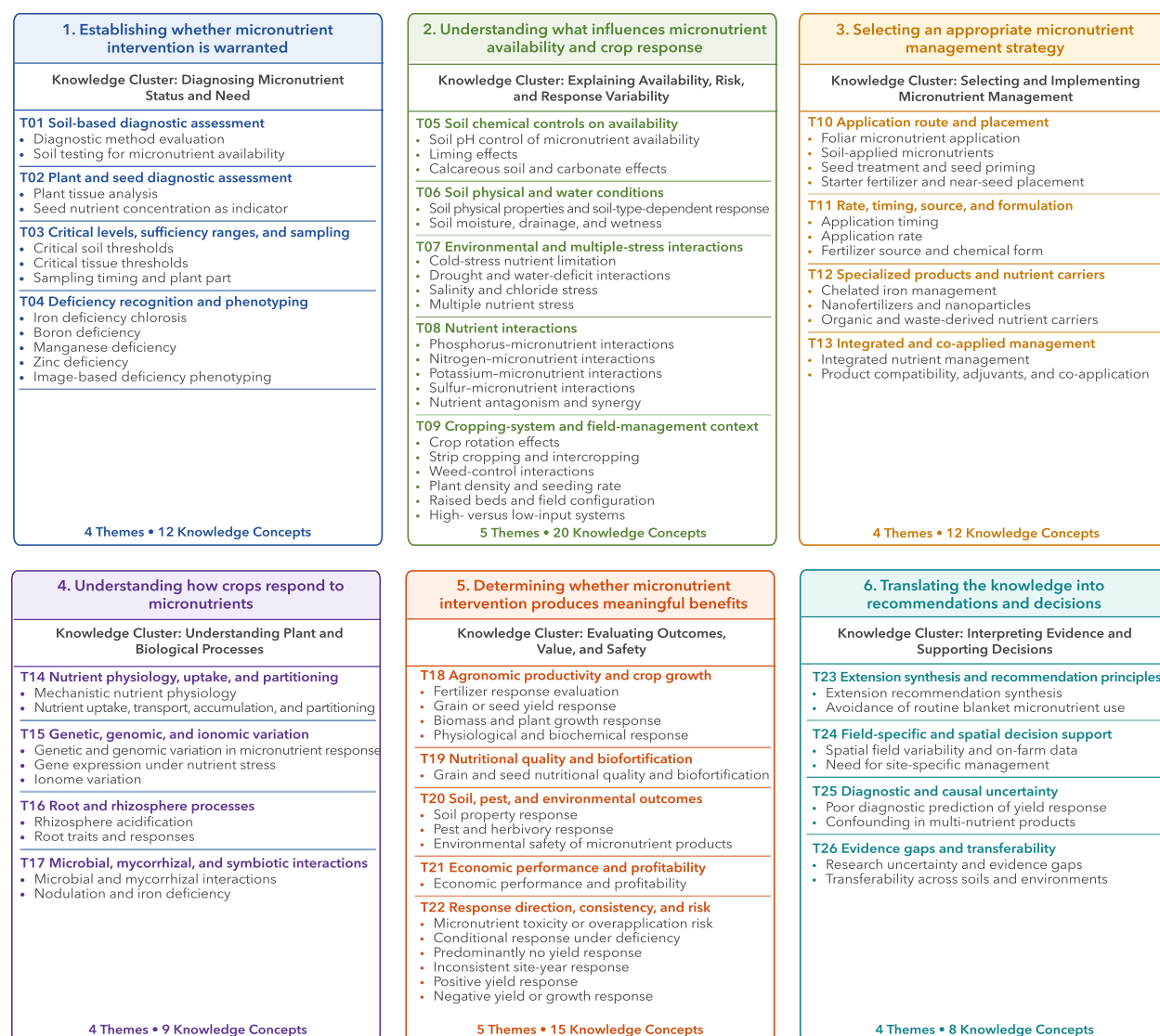


Figure 1B. Complete knowledge architecture showing the six decision pathway components, their corresponding knowledge clusters, 26 themes, and 76 knowledge concepts used to organize the micronutrient knowledge synthesis.

## Developing the knowledge architecture

A structured, researcher-directed, generative artificial intelligence (AI)-assisted knowledge synthesis drawing on thematic analysis methods was used to analyze the 126 Ontario-relevant records. The synthesis used only information contained in the systematic-map dataset and deep extraction of the Ontario-relevant records. Evidence from mixed-crop records was included only where findings relevant to corn or soybean could be distinguished.

The analysis moved iteratively from detailed extracted information to higher-order concepts. Titles, abstracts, extracted evidence, key insights, production context, outcomes, micronutrients, crops and other substantive fields were reviewed to identify recurring concepts. Open coding was used to identify initial concepts, after which conceptually similar or overlapping codes were consolidated while retaining meaningful distinctions. This

produced 76 Knowledge Concepts, which were organized into 26 Themes and six Knowledge Clusters corresponding to the six Decision Pathway Components.

The developing architecture was assessed iteratively for coverage, traceability and conceptual coherence. Concepts and themes were reviewed to determine whether they adequately represented the knowledge base, remained sufficiently distinct from one another and could be traced to the underlying extracted information. The architecture was refined through this process before being adopted for the final synthesis.

Evidence profiles were subsequently generated for the decision pathway components, clusters and themes. Frequencies were used to identify where information was concentrated within the knowledge base; they were not treated as measures of evidence quality, effect size or certainty. The synthesis retained positive, negative, mixed, neutral and no-response findings and distinguished among different types of outcomes rather than treating all measured responses as equivalent.

Finally, theme co-occurrence and knowledge cluster connectivity analyses were used to examine relationships across the knowledge architecture. These analyses are presented after the six knowledge clusters have been examined individually and are used to reconnect the separate parts of the applied pathway.

The systematic-map characterization and deep-extraction datasets that provided the evidence base for the synthesis were developed through the AI-assisted extraction and classification process described in the companion systematic-map report, including application of the Geographic Tier/Ontario-relevance framework.

Generative artificial intelligence (AI) was used as an analytical support tool in the knowledge synthesis. AI supported concept identification and open coding; code consolidation; development and iterative refinement of the Knowledge Concepts, Themes, Knowledge Clusters and Decision Pathway Components; evidence profiling; interpretive synthesis across records, themes and clusters; and the co-occurrence and connectivity analyses used to examine relationships within the knowledge architecture. AI-assisted analysis was researcher-directed and governed by explicit analytical instructions, coding rules and controlled vocabularies. Generative AI was not treated as an independent source of evidence: analytical outputs were required to be grounded in the systematic-map dataset and extracted information rather than external information introduced by the AI. AI-generated classifications, patterns and interpretations were treated as provisional. Emerging outputs were reviewed against the underlying extracted information, challenged for conceptual and evidentiary consistency, and revised or rejected where necessary. The researcher retained responsibility for the analytical framework, interpretation of the evidence and all final analytical decisions.

## Orientation to the Ontario-relevant knowledge architecture

Before considering the individual areas of the applied pathway, it is useful to understand the overall structure of the Ontario-relevant knowledge architecture. The 126 records do not provide equal coverage of every knowledge cluster, theme, micronutrient or crop. Some parts of the pathway have substantial amounts of information, while others are comparatively thin. The ability of the knowledge base to inform a particular decision therefore depends both on the type of decision being considered and on the micronutrient involved.

### Distribution of knowledge across the decision pathway

The themes are unevenly represented across the Ontario-relevant records. Some parts of the decision pathway appear in many records, while others appear in comparatively few. These differences matter because the ability to support a micronutrient decision depends not simply on the total amount of available information, but on whether the particular types of knowledge required for that decision are available.

Information was most strongly concentrated around crop response and management. Agronomic Productivity and Crop Growth (T18) appeared in 102 of the 126 records (81%), while Response Direction, Consistency, and Risk (T22) occurred in 63 records (50%). Nutrient Physiology, Uptake, and Partitioning (T14) and Application Route and Placement (T10) were similarly prominent, occurring in 62 (49.2%) and 61 (48.4%) records, respectively (Figure 2).

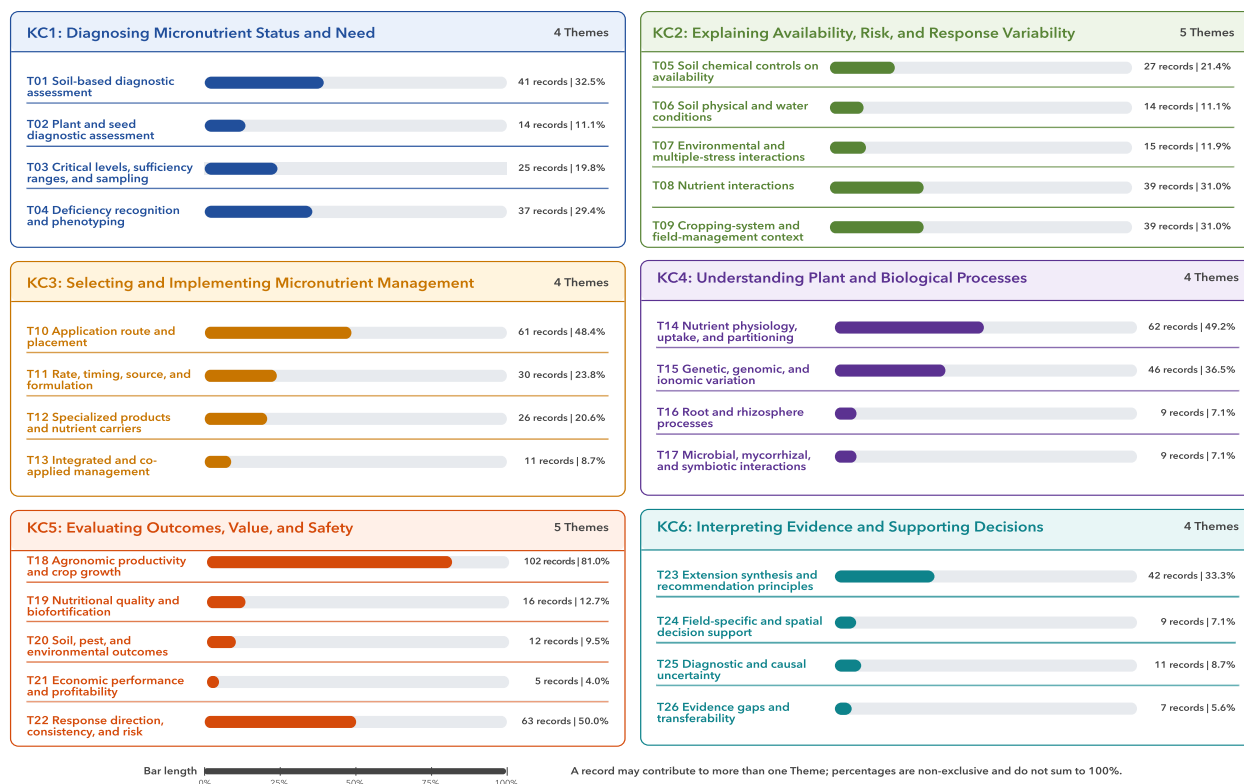


Figure 2. Theme frequency and distribution across the 126 Ontario-relevant records. Bars show the percentage of records assigned to each Theme, grouped by Knowledge Cluster; labels report both the number and percentage of records. Because a record can contribute to more than one theme, percentages are non-exclusive and do not sum to 100%.

Collectively, these concentrations mean that the Ontario-relevant knowledge contains substantial information about what happens to crops under different micronutrient conditions, how nutrients are taken up and distributed within plants, how micronutrients have been applied, and whether responses are positive, absent, mixed or inconsistent.

Other parts of the decision pathway are represented in considerably fewer records. Economic Performance and Profitability, Field-specific and Spatial Decision Support, Root and Rhizosphere Processes, and Microbial, Mycorrhizal, and Symbiotic Interactions were each represented by relatively few records, while Evidence Gaps and Transferability was also sparsely represented. These areas are not necessarily less important. Rather, their limited representation shows that fewer records in this knowledge base address the economic value, field specificity and transferability of crop responses.

Figure 2 therefore shows a structural imbalance in the documented knowledge: more records address crop response and management than the economic value, field specificity and transferability of those responses. The architecture consequently shows greater thematic coverage in some parts of the decision pathway than in others.

## Differences in thematic coverage among micronutrients

The unevenness of the knowledge architecture also extends across micronutrients. A theme that is well represented across the 126 records does not necessarily contain comparable information for all nine micronutrients. The ability to support a particular management decision therefore depends both on the type of decision being considered and on the micronutrient involved.

Zinc had the broadest coverage across the knowledge architecture, appearing across diagnostic, management, plant-process and outcome themes. Iron and manganese also had broad thematic coverage, although their profiles differed: iron was particularly prominent in areas involving nutrient physiology, genetic and ionic variation, deficiency recognition and agronomic outcomes, while manganese extended across management, nutrient interactions, diagnosis and crop-response themes. Boron and copper were represented across several parts of the pathway but at lower overall volumes (Figure 3).

Molybdenum had considerably less thematic coverage, while chlorine/chloride, nickel and cobalt were particularly sparsely represented. These differences place an important boundary around the synthesis. The presence of a finding within a well-developed theme does not mean that the same depth of information exists for every micronutrient. Conversely, little or no information at a particular micronutrient-theme intersection indicates a gap in the documented knowledge; it does not demonstrate that the underlying relationship or response does not occur.

The micronutrient profiles therefore show different patterns and extents of thematic coverage, rather than one uniformly represented body of micronutrient knowledge. Figure 3 shows where more or fewer records address particular micronutrients and decision areas. It does not measure evidence quality, effect size, agreement among findings or readiness for recommendation.



Figure 3. Micronutrient × Theme Knowledge Heat Map. Cell values show the number of records addressing each micronutrient-theme intersection across the dataset. Counts are non-exclusive because a record may address multiple micronutrients and multiple themes.

## Moving from the architecture to the applied pathway

The Ontario-relevant records are unevenly distributed in two dimensions: some parts of the decision pathway appear in more records than others, and thematic coverage differs among micronutrients. These differences need to remain visible throughout the synthesis.

The six knowledge clusters provide a way to examine this uneven knowledge systematically. The pathway begins with the information needed to establish whether a micronutrient deficiency exists or intervention may be warranted. Subsequent components address the conditions affecting availability and response, management options, crop and biological responses, meaningful outcomes, and the interpretation of knowledge for decisions.

The following section begins with the first Decision Pathway Component: establishing how micronutrient status and the need for intervention can be identified and diagnosed in corn and soybean.

# Establishing whether micronutrient intervention is warranted

## Knowledge Cluster: Diagnosing Micronutrient Status and Need

Establishing whether intervention is warranted begins with determining whether there is credible evidence of a micronutrient deficiency. The knowledge base shows that this is rarely established by a single test, threshold, or symptom. Soil tests, plant and seed analyses, critical levels and sufficiency ranges, visual symptoms, and phenotyping provide different and complementary information about micronutrient status and deficiency risk.

The Diagnosing Micronutrient Status and Need Knowledge Cluster contains 64 records organized into four themes: Soil-based Diagnostic Assessment (T01), Plant and Seed Diagnostic Assessment (T02), Critical Levels, Sufficiency Ranges, and Sampling (T03), and Deficiency Recognition and Phenotyping (T04).

### Knowledge Cluster at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                                                                                                                                                    |
|---------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Decision Pathway Component</b>           | Establishing whether micronutrient intervention is warranted                                                                                                                                               |
| <b>What this cluster addresses</b>          | How soil tests, plant and seed measurements, critical levels, sampling practices, and deficiency indicators can be used together to assess micronutrient status and whether intervention may be warranted. |
| <b>Records</b>                              | 64                                                                                                                                                                                                         |
| <b>Themes</b>                               | T01 Soil-based Diagnostic Assessment; T02 Plant and Seed Diagnostic Assessment; T03 Critical Levels, Sufficiency Ranges, and Sampling; T04 Deficiency Recognition and Phenotyping                          |
| <b>Crop profile</b>                         | Soybean (33); Corn (27); Corn & Soybean (4)                                                                                                                                                                |
| <b>Most represented micronutrients</b>      | Iron (37); Zinc (36); Manganese (29); Boron (27); Copper (22)                                                                                                                                              |
| <b>Most represented research approaches</b> | Guidance/extension (26); Field experiment (23); Lab study (7); Greenhouse study (4)                                                                                                                        |

### Key Evidence Message

Micronutrient diagnosis requires multiple, complementary indicators rather than reliance on a single soil or tissue value.

The different forms of diagnostic information answer different parts of the problem. Soil measurements characterize extractable nutrient supply and conditions associated with deficiency risk. Plant and seed measurements provide information about nutrient status and uptake. Critical levels, sufficiency ranges, and sampling protocols provide the framework needed to interpret those measurements. Visual symptoms and phenotypic indicators show how nutrient stress is expressed in the crop.

A central distinction runs through the cluster: identifying a micronutrient deficiency or nutritional status is not the same as predicting a beneficial response to intervention. The relationship between diagnostic indicators and crop response varies with the micronutrient, crop, genotype, sampling method, growth stage, environment, and soil context. Diagnostic information is therefore most useful when multiple indicators are considered together and interpreted within the conditions of the individual field.

## Soil-based diagnostic assessment

### Theme at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                                                                            |
|---------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------|
| <b>Theme focus</b>                          | Use and evaluation of soil tests, extractants, and soil-test indicators to estimate micronutrient availability or fertilizer need. |
| <b>Records</b>                              | 41                                                                                                                                 |
| <b>Knowledge Concepts</b>                   | Diagnostic method evaluation; Soil testing for micronutrient availability                                                          |
| <b>Crop profile</b>                         | Corn (21); Soybean (16); Corn & Soybean (4)                                                                                        |
| <b>Most represented micronutrients</b>      | Zinc (28); Boron (23); Manganese (21); Iron (20); Copper (18)                                                                      |
| <b>Most represented research approaches</b> | Guidance/extension (25); Field experiment (10); Observational/diagnostic/testing study (3); Lab study (2)                          |

### Key Evidence Message

Soil tests characterize extractable nutrient supply and risk conditions, but calibration to crop response is uneven.

Soil testing provides an important starting point for assessing micronutrient supply and identifying conditions associated with greater deficiency risk. The knowledge base supports using soil testing as a screening and interpretive tool, but shows that soil-test values alone do not consistently predict whether micronutrient application will increase yield. The field evidence illustrates why this distinction matters. Study 222 reported no corn or soybean grain-yield response to soil- or foliar-applied micronutrients in any trial or year. Study 844

similarly found that foliar fertilization sometimes increased leaf nutrient concentrations and often increased grain concentrations without increasing soybean yield. Relationships between soil and tissue tests were also poor or not significant. These findings show that differences in nutrient supply or plant nutrient concentration do not necessarily identify a yield-responsive condition.

Responses can occur where a specific deficiency is clearly expressed. Study 188 found that in-furrow ferric ethylenediamine-N,N'-bis(2-hydroxyphenylacetic acid) (Fe-EDDHA) increased yield of a soybean variety susceptible to iron deficiency chlorosis (IDC) under moderate to severe IDC on calcareous soils. However, soil organic matter, pH, electrical conductivity, and diethylenetriaminepentaacetic acid (DTPA)-extractable iron were poor predictors of IDC severity. Together, these findings show why soil measurements need to be interpreted in relation to the specific deficiency, crop, and field conditions rather than used alone to determine whether treatment is warranted.

## Plant and seed diagnostic assessment

### Theme at a Glance

| CHARACTERISTIC                       | SUMMARY                                                                                                                         |
|--------------------------------------|---------------------------------------------------------------------------------------------------------------------------------|
| Theme focus                          | Use of tissue, plant, or seed nutrient measurements as indicators of crop micronutrient status, resistance, or likely response. |
| Records                              | 14                                                                                                                              |
| Knowledge Concepts                   | Plant tissue analysis; Seed nutrient concentration as indicator                                                                 |
| Crop profile                         | Corn (7); Soybean (7)                                                                                                           |
| Most represented micronutrients      | Iron (11); Zinc (10); Manganese (9); Copper (7); Boron (6)                                                                      |
| Most represented research approaches | Field experiment (7); Guidance/extension (5); Lab study (1); Observational/diagnostic/testing study (1)                         |

### Key Evidence Message

Plant tissue and seed analyses reveal nutrient status, uptake, and ionic differences.

Plant and seed analyses provide another perspective on micronutrient status by showing what nutrients have been taken up and accumulated by the crop. However, measured concentrations can vary with plant part, sampling time, genotype, and environment. Nutrient concentration therefore needs to be interpreted within this context rather than automatically treated as evidence that fertilizer is required. Plant tissue measurements can contribute

directly to assessment of crop nutrient status, while seed analyses provide additional information about nutrient accumulation and variation among genotypes and environments.

Study 1009 demonstrated substantial variation in seed concentrations of zinc, iron, copper, and manganese across 90 soybean genotypes. Study 755 similarly found that zinc and manganese seed concentrations varied markedly among locations and that iron concentrations differed among soybean genotypes classified as susceptible, moderately resistant, or resistant to iron deficiency. These findings demonstrate that genotype and environment can influence nutrient concentrations and need to be considered when interpreting plant and seed measurements.

Sampling practices can also influence diagnostic results. Study 227 provides a complementary caution: tissue micronutrient concentrations were considered adequate in recent Ohio trials in which micronutrient fertilization did not produce a grain-yield response. Plant and seed analyses can therefore provide valuable information about nutrient status, but measured concentrations should not be assumed to indicate fertilizer-responsive deficiency.

## Critical levels, sufficiency ranges, and sampling

### Theme at a Glance

| CHARACTERISTIC                       | SUMMARY                                                                              |
|--------------------------------------|--------------------------------------------------------------------------------------|
| Theme focus                          | Thresholds and sampling rules used to interpret soil and plant diagnostic results.   |
| Records                              | 25                                                                                   |
| Knowledge Concepts                   | Critical soil thresholds; Critical tissue thresholds; Sampling timing and plant part |
| Crop profile                         | Corn (15); Soybean (6); Corn & Soybean (4)                                           |
| Most represented micronutrients      | Zinc (19); Manganese (16); Boron (15); Copper (13); Iron (11)                        |
| Most represented research approaches | Guidance/extension (16); Field experiment (6); Lab study (2); Greenhouse study (1)   |

### Key Evidence Message

Critical levels and sufficiency ranges are method- and context-dependent.

Diagnostic measurements become useful for decisions only when there is a basis for interpreting them. Critical levels and sufficiency ranges provide such reference points, but the knowledge base shows that these values are not necessarily transferable among methods, regions, or production conditions. Sampling time, crop growth stage, tissue selection,

extraction method, and regional calibration can all affect their interpretation.

Study 1134 provides a practical example. For corn in Ohio, soil pH generally needs to be above 6.6 and soil-test zinc below 4 ppm before a yield response to additional zinc would be expected. This provides a concrete diagnostic threshold, but one explicitly associated with a particular crop and regional recommendation context rather than a universal value.

Sampling practices are equally important. Study 805 found that foliar manganese, iron, and zinc concentrations varied with time of day. Study 844 further found that relationships between systematically collected soil and tissue tests were poor or not significant across 42 soybean sites. Together, these findings reinforce the importance of interpreting critical levels and sufficiency ranges in relation to the method, sampling protocol, crop stage, and calibration context in which they were developed.

## Deficiency recognition and phenotyping

### Theme at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                                                                                           |
|---------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Theme focus</b>                          | Recognition and characterization of specific micronutrient deficiencies using symptoms, severity ratings, images, or other phenotypic indicators. |
| <b>Records</b>                              | 37                                                                                                                                                |
| <b>Knowledge Concepts</b>                   | Iron deficiency chlorosis; Boron deficiency; Manganese deficiency; Zinc deficiency; Image-based deficiency phenotyping                            |
| <b>Crop profile</b>                         | Soybean (23); Corn (14)                                                                                                                           |
| <b>Most represented micronutrients</b>      | Iron (23); Zinc (13); Boron (12); Manganese (11); Copper (6)                                                                                      |
| <b>Most represented research approaches</b> | Guidance/extension (16); Field experiment (10); Lab study (7); Greenhouse study (2)                                                               |

### Key Evidence Message

Micronutrient diagnosis requires multiple, complementary indicators rather than reliance on a single soil or tissue value.

Micronutrient problems can also be identified through the way nutrient stress is expressed in the crop. Approaches range from visual symptoms and severity ratings to image-based and genetic phenotyping. The extent of documented information differs substantially among micronutrients. Soybean iron deficiency chlorosis is more extensively represented in the knowledge base, while other deficiencies have fewer field-based characterizations.

Study 188 illustrates the comparatively well-developed characterization of soybean IDC. Severity ranged from low to severe within calcareous-soil field sites, and the study compared tolerant and susceptible soybean varieties together with management approaches intended to mitigate IDC. Genetic analyses offer a different way to investigate variation associated with iron efficiency. Study 1164 identified a quantitative trait locus for soybean seed iron accumulation that explained 21.5% of the variation and reported a potential genetic link between seed iron accumulation and iron efficiency.

Other micronutrients show more conditional patterns. Study 909 reported a soybean yield increase from manganese sulfate at one site-year where plants were manganese deficient, while manganese application did not affect yield at the other three site-years. Study 1160 identifies soil conditions associated with greater manganese-deficiency risk and provides tissue sufficiency ranges for corn and soybean, but also reports no yield increase from manganese application across the summarized Minnesota grain-yield sites.

Deficiency symptoms and phenotypic indicators can therefore strengthen a diagnosis, particularly where the deficiency is well characterized, but they still need to be interpreted alongside field conditions and other diagnostic information.

## Implications for micronutrient decisions

Establishing whether intervention is warranted requires more than identifying a low nutrient concentration or observing a possible deficiency symptom. Across the four diagnostic themes, different forms of information address different parts of the diagnostic problem. Soil assessment characterizes nutrient supply and conditions associated with deficiency risk; plant tissue analysis provides information about crop nutrient status; critical levels and sampling protocols provide a basis for interpreting those measurements; and deficiency symptoms and phenotyping show how nutrient stress is expressed by the crop.

These forms of information are complementary rather than interchangeable. A soil or tissue measurement can indicate nutrient status without demonstrating that fertilizer application will increase yield, while a visible or phenotypic response needs to be interpreted in relation to the nutrient involved and the conditions under which it occurs. The synthesis therefore supports diagnosis based on the convergence of multiple indicators and their interpretation within the crop and production context, rather than reliance on a single measurement, threshold or symptom.

A further distinction is critical for management: diagnosing a micronutrient deficiency establishes a reason to consider intervention; it does not establish that intervention will produce an agronomic or economic benefit. The likelihood of response depends on why the deficiency has occurred, whether the nutrient can be made available to the crop, and the soil, environmental and management conditions affecting response.

The next Knowledge Cluster therefore moves from identifying a possible micronutrient deficiency to understanding the conditions that create deficiency risk and determine whether a crop is likely to respond.

## Understanding what influences micronutrient availability and crop response

### Knowledge Cluster: Explaining Availability, Risk, and Response Variability

Micronutrient availability and crop response are not determined by nutrient supply alone. Whether a nutrient is available to the crop—and whether intervention produces a measurable benefit—depends on the interaction of soil properties, environmental conditions, other nutrients, and field-management practices. The Explaining Availability, Risk, and Response Variability Knowledge Cluster contains 85 records organized into five themes: Soil Chemical Controls on Availability (T05), Soil Physical and Water Conditions (T06), Environmental and Multiple-Stress Interactions (T07), Nutrient Interactions (T08), and Cropping-System and Field-Management Context (T09).

#### Knowledge Cluster at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                                                                                                                                                                                          |
|---------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Decision Pathway Component</b>           | Understanding what influences micronutrient availability and crop response                                                                                                                                                                       |
| <b>What this cluster addresses</b>          | How soil chemistry, soil physical and water conditions, environmental stresses, nutrient interactions, and cropping-system and field-management context influence micronutrient availability, deficiency risk, and variability in crop response. |
| <b>Records</b>                              | 85                                                                                                                                                                                                                                               |
| <b>Themes</b>                               | T05 Soil Chemical Controls on Availability; T06 Soil Physical and Water Conditions; T07 Environmental and Multiple-Stress Interactions; T08 Nutrient Interactions; T09 Cropping-System and Field-Management Context                              |
| <b>Crop profile</b>                         | Corn (50); Soybean (31); Corn & Soybean (4)                                                                                                                                                                                                      |
| <b>Most represented micronutrients</b>      | Zinc (54); Iron (44); Manganese (44); Copper (36); Boron (27)                                                                                                                                                                                    |
| <b>Most represented research approaches</b> | Field experiment (42); Guidance/extension (19); Greenhouse study (12); Lab study (10)                                                                                                                                                            |

#### Key Evidence Message

Micronutrient availability, deficiency risk and crop response are shaped by interacting soil, environmental, nutrient, and management conditions.

The Knowledge Cluster helps explain why micronutrient deficiency risk and crop response vary among fields and production environments. Soil chemistry and physical conditions

influence whether nutrients remain available and accessible to roots. Environmental stresses can alter nutrient demand and uptake, while interactions with other nutrients can increase or decrease availability. Rotation, plant density, field configuration, and other management choices add another layer of variability.

The central message is conditionality. A micronutrient treatment that performs well under one combination of soil, crop, environmental, and management conditions cannot be assumed to perform similarly elsewhere. Understanding the conditions that create deficiency risk or favour response is therefore essential both for interpreting diagnostic information and for deciding whether intervention is likely to be worthwhile.

## Soil chemical controls on availability

### Theme at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                                                          |
|---------------------------------------------|------------------------------------------------------------------------------------------------------------------|
| <b>Theme focus</b>                          | Effects of pH, liming, carbonates, and related soil chemistry on micronutrient availability and deficiency risk. |
| <b>Records</b>                              | 27                                                                                                               |
| <b>Knowledge Concepts</b>                   | Soil pH control of micronutrient availability; Liming effects; Calcareous soil and carbonate effects             |
| <b>Crop profile</b>                         | Corn (14); Soybean (12); Corn & Soybean (1)                                                                      |
| <b>Most represented micronutrients</b>      | Iron (18); Zinc (15); Manganese (13); Boron (10); Copper (9)                                                     |
| <b>Most represented research approaches</b> | Guidance/extension (10); Field experiment (7); Lab study (5); Greenhouse study (4)                               |

### Key Evidence Message

Soil pH, liming, carbonate, and bicarbonate conditions are important chemical influences on micronutrient availability, particularly for iron, manganese, and zinc.

Soil chemistry strongly influences whether micronutrients remain in forms that crops can access. The evidence particularly highlights soil pH, liming, carbonate, and bicarbonate conditions as controls on iron, manganese, and zinc availability. These factors also interact: management intended to address one soil deficiency can alter the availability of other nutrients. Micronutrient status therefore needs to be interpreted within the broader soil-chemistry context.

Study 188 illustrates the complexity of diagnosing soybean iron deficiency chlorosis on calcareous Mollisols. Soil organic matter, pH, electrical conductivity, and DTPA-extractable iron were poor predictors of IDC severity, even though in-furrow Fe-EDDHA increased yield

of a susceptible variety where IDC was moderate to severe. Study 1160 identifies a related pH effect for manganese, with greater deficiency risk on heavily weathered sandy soils and peat or organic soils above pH 6.0, and on calcareous mineral soils at pH 6.5 or above.

Zinc provides another example of this conditionality. Study 1134 indicates that, for corn in Ohio, soil pH generally needs to be above 6.6 and soil-test zinc below 4 ppm before a yield response to additional zinc would be expected. Study 843 found positive relationships between soybean yield and soil-test zinc and negative relationships between yield and soil pH across site-years in two Minnesota fields.

Together, these findings show that micronutrient availability cannot be interpreted from nutrient concentration alone. Soil chemical conditions help determine whether the nutrient is accessible and whether a crop response is plausible.

## Soil physical and water conditions

### Theme at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                                                                               |
|---------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------|
| <b>Theme focus</b>                          | Effects of soil type, texture, organic matter, drainage, wetness, and moisture conditions on micronutrient availability and response. |
| <b>Records</b>                              | 14                                                                                                                                    |
| <b>Knowledge Concepts</b>                   | Soil physical properties and soil-type-dependent response; Soil moisture, drainage, and wetness                                       |
| <b>Crop profile</b>                         | Corn (9); Soybean (4); Corn & Soybean (1)                                                                                             |
| <b>Most represented micronutrients</b>      | Zinc (9); Manganese (8); Iron (7); Copper (6); Boron (5)                                                                              |
| <b>Most represented research approaches</b> | Field experiment (4); Guidance/extension (4); Greenhouse study (3); Lab study (2)                                                     |

### Key Evidence Message

Soil type and physical root-zone conditions influence micronutrient supply, root access and deficiency risk.

Soil type and physical condition influence both nutrient supply and the ability of roots to access that supply. Texture, organic matter, drainage, wetness, and soil moisture can therefore change deficiency risk and the likelihood of response to treatment. The available information shows different response patterns among sandy, calcareous, poorly drained, eroded, and organic soils.

Study 209 illustrates how strongly soil type can affect recommendations. Copper is not recommended for Minnesota mineral soils because documented crop response is lacking,

while soil testing on organic soils is described as the best predictor of whether copper is needed in a fertilizer program. Study 221 examined corn and soybean on an Iowa sandy soil and found no grain-yield response to boron, manganese, or zinc; the available soil-test zinc interpretation correctly predicted the absence of a zinc response.

Within-field conditions also matter. Study 1177 describes soybean IDC management specifically for affected areas of fields and notes that iron becomes less soluble as soil pH increases, particularly in soils containing substantial calcium carbonate. Study 188 likewise documented IDC severity ranging from low to severe within calcareous-soil field sites.

These examples show why soil type and water conditions should be treated as part of the diagnostic and response context, rather than as a universal basis for micronutrient treatment.

## Environmental and multiple-stress interactions

### Theme at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                                                                          |
|---------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|
| <b>Theme focus</b>                          | Effects of cold, drought, salinity, chloride, and combined nutrient stresses on micronutrient limitation or management response. |
| <b>Records</b>                              | 15                                                                                                                               |
| <b>Knowledge Concepts</b>                   | Cold-stress nutrient limitation; Drought and water-deficit interactions; Salinity and chloride stress; Multiple nutrient stress  |
| <b>Crop profile</b>                         | Corn (10); Soybean (5)                                                                                                           |
| <b>Most represented micronutrients</b>      | Zinc (10); Iron (8); Manganese (7); Boron (4); Copper (4)                                                                        |
| <b>Most represented research approaches</b> | Lab study (5); Guidance/extension (5); Greenhouse study (4); Field experiment (1)                                                |

### Key Evidence Message

Cold, drought, salinity, and combined nutrient stress can alter root function and nutrient demand.

Micronutrient limitations can become more apparent—or change in their expression—when crops experience other stresses. Cold, drought, salinity, and combined nutrient deficiencies can affect root function, nutrient acquisition, and nutrient demand. This makes environmental context important when interpreting both deficiency symptoms and responses to management. At the same time, biological responses observed under controlled stress conditions do not necessarily predict yield benefits under field conditions.

Study 898 provides a field example involving cold conditions in maize. Early conditions were dry and relatively cold, and phosphorus deficiency associated with cold weather affected

early nutrient uptake. Slurry injection with a nitrification inhibitor increased early phosphorus, zinc, and manganese concentrations and improved zinc and manganese status, showing that nutrient response depended partly on the environmental conditions under which acquisition occurred.

Study 276 demonstrates that interactions among stresses can also alter the biological response itself. Soybean leaves and roots responded to both iron and phosphate deficiency within 24 hours, and thousands of genes either changed the direction of their expression after a second stress or became differentially expressed only after the second stress was imposed.

The practical implication is that micronutrient stress does not necessarily operate independently. Environmental and nutrient stresses can interact in ways that change nutrient uptake and crop response, making results from a single stress condition difficult to transfer directly to other production environments.

## Nutrient interactions

### Theme at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                                                                                                                              |
|---------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Theme focus</b>                          | Antagonistic, synergistic, or modifying effects among phosphorus, nitrogen, potassium, sulfur, micronutrients, and co-applied products.                                              |
| <b>Records</b>                              | 39                                                                                                                                                                                   |
| <b>Knowledge Concepts</b>                   | Phosphorus-micronutrient interactions; Nitrogen-micronutrient interactions; Potassium-micronutrient interactions; Sulfur-micronutrient interactions; Nutrient antagonism and synergy |
| <b>Crop profile</b>                         | Corn (25); Soybean (13); Corn & Soybean (1)                                                                                                                                          |
| <b>Most represented micronutrients</b>      | Zinc (28); Manganese (22); Copper (19); Iron (19); Boron (12)                                                                                                                        |
| <b>Most represented research approaches</b> | Field experiment (23); Greenhouse study (6); Guidance/extension (6); Lab study (4)                                                                                                   |

### Key Evidence Message

Micronutrient availability and response can be modified by other nutrients and co-applied inputs, producing beneficial, neutral or antagonistic interactions.

Micronutrients function within the broader fertility program rather than as isolated inputs. Phosphorus, nitrogen, potassium, sulfur, other micronutrients, and co-applied products can alter micronutrient availability, uptake, and response. Depending on the combination and production context, these interactions can be beneficial, neutral, or antagonistic.

Study 1063 demonstrates this interaction in maize. Across rotation systems and nitrogen rates, increasing nitrogen was associated with greater copper uptake, while nitrogen application also produced dilution effects on stover zinc and magnesium concentrations. Study 1185 similarly found that plant density and nitrogen rate influenced whole-plant nutrient contents: grain iron and zinc were primarily influenced by nitrogen rate, while manganese and copper were affected by the interaction of plant density and nitrogen rate.

Interactions also extend beyond conventional nutrient combinations. Study 1009 identified positively correlated groups of elements in soybean seed, including relationships between zinc and phosphorus and sulfur, and between zinc and copper, selenium, and rubidium. Study 893, conducted in Ontario, found that some manganese formulations tank-mixed with glyphosate antagonized weed control under some conditions and that two combinations reduced soybean yield relative to glyphosate alone. Sequential rather than simultaneous application was recommended.

Micronutrient decisions therefore need to account for the full nutrient and input system. A response attributed to one nutrient may depend partly on the supply, form, or management of another input.

## Cropping-system and field-management context

### Theme at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                                                                                                                                 |
|---------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Theme focus</b>                          | Effects of rotation, intercropping, weed control, plant density, field configuration, and production intensity on micronutrient status or response.                                     |
| <b>Records</b>                              | 39                                                                                                                                                                                      |
| <b>Knowledge Concepts</b>                   | Crop rotation effects; Strip cropping and intercropping; Weed-control interactions; Plant density and seeding rate; Raised beds and field configuration; High- versus low-input systems |
| <b>Crop profile</b>                         | Corn (19); Soybean (16); Corn & Soybean (4)                                                                                                                                             |
| <b>Most represented micronutrients</b>      | Zinc (24); Manganese (20); Copper (18); Iron (18); Boron (15)                                                                                                                           |
| <b>Most represented research approaches</b> | Field experiment (26); Guidance/extension (11); Observational/diagnostic/testing study (2)                                                                                              |

### Key Evidence Message

Rotation, intercropping, weed control, population, field configuration, and input intensity modify nutrient uptake and measured response.

Cropping-system and field-management decisions can change micronutrient status and the way crops respond to intervention. Rotation, intercropping, weed control, plant population, field configuration, and overall input intensity influence nutrient uptake or the measured effect of micronutrient treatments. These factors help explain variability among production settings, but they should not themselves be treated as universal micronutrient prescriptions. Importantly, these management practices form part of the production context in which micronutrient decisions are made; they are distinct from the micronutrient application strategies examined in the next Knowledge Cluster.

Study 1063 provides a long-term Canadian example. In Ottawa, maize grown in maize-alfalfa, maize-soybean, and continuous-maize rotations differed in micronutrient accumulation. Total magnesium, zinc, and copper content was greatest in maize following alfalfa, intermediate following soybean, and lowest in continuous maize, while iron uptake was lowest in the maize-alfalfa rotation. Study 1185 demonstrates another management effect: plant density and nitrogen rate significantly influenced whole-plant nutrient contents, and their interaction affected manganese and copper content in grain.

Management can also alter the success of interventions intended to address an identified deficiency. Study 188 found that an oat companion crop consistently increased yield of an IDC-susceptible soybean variety under severe IDC, but sometimes reduced yield when oat growth exceeded 25 cm. Study 194 provides a contrasting example: no single additional input in a high- versus low-input soybean management comparison significantly increased grain yield where visible nutrient deficiencies and foliar disease were minimal.

These examples reinforce that management context can alter micronutrient uptake and crop response, but greater management intensity does not in itself create a need for micronutrient intervention.

## Implications for micronutrient decisions

Once a possible micronutrient deficiency has been identified, the next step is understanding the conditions that may be causing it and determining whether those conditions make a crop response more or less likely.

Across the five themes, the knowledge base shows that micronutrient availability, deficiency risk, and crop response result from interacting conditions rather than a single factor. Soil chemistry affects nutrient solubility and availability. Soil physical and water conditions affect root access. Environmental stresses can change nutrient demand and uptake. Other nutrients and co-applied products can produce synergistic or antagonistic interactions. Cropping-system and management decisions further modify nutrient uptake and measured response.

The illustrative evidence helps explain why micronutrient responses can be inconsistent among locations and years. Higher pH and carbonate conditions can increase the risk of iron, manganese, or zinc limitations, yet individual soil measurements may still be poor predictors of deficiency severity. Cold conditions can alter early nutrient acquisition, multiple stresses

can change biological responses, nitrogen and plant density can affect micronutrient accumulation, and rotation or companion crops can modify both uptake and yield outcomes.

The practical message is that the likelihood of micronutrient response is field- and context-dependent. A response observed under one combination of soil, environmental, crop, nutrient, and management conditions should not automatically be transferred to another. Understanding these conditions helps explain why a micronutrient deficiency occurs and identify situations in which a response may be more or less plausible, but it does not necessarily allow the magnitude or consistency of crop response to be predicted. It moves the decision from simply asking whether a deficiency may exist to asking whether the production context provides a credible basis for expecting a response.

Once the conditions affecting availability and response are understood, attention can turn to how intervention should be implemented. The next Knowledge Cluster, Selecting and Implementing Micronutrient Management, examines application route and placement, rate and timing, fertilizer source and formulation, specialized products, and the integration of micronutrients with other management practices.

# Selecting an appropriate micronutrient management strategy

## Knowledge Cluster: Selecting and Implementing Micronutrient Management

Once there is a credible basis for intervention, the next challenge is deciding how the micronutrient should be managed. Selecting a product is only one part of that decision. Application route, placement, rate, timing, nutrient source, formulation, product compatibility, and the broader fertility and crop-management program can all influence the outcome. The Selecting and Implementing Micronutrient Management Knowledge Cluster contains 80 records organized into four themes: Application Route and Placement (T10), Rate, Timing, Source, and Formulation (T11), Specialized Products and Nutrient Carriers (T12), and Integrated and Co-applied Management (T13).

### Knowledge Cluster at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                                                                                                                                                                                            |
|---------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Decision Pathway Component</b>           | Selecting an appropriate micronutrient management strategy                                                                                                                                                                                         |
| <b>What this cluster addresses</b>          | How micronutrients are delivered and integrated into corn and soybean production systems, including application route and placement; rate, timing, source, and formulation; specialized products and nutrient carriers; and co-applied management. |
| <b>Records</b>                              | 80                                                                                                                                                                                                                                                 |
| <b>Themes</b>                               | T10 Application Route and Placement; T11 Rate, Timing, Source, and Formulation; T12 Specialized Products and Nutrient Carriers; T13 Integrated and Co-applied Management                                                                           |
| <b>Crop profile</b>                         | Corn (44); Soybean (31); Corn & Soybean (5)                                                                                                                                                                                                        |
| <b>Most represented micronutrients</b>      | Zinc (53); Manganese (41); Boron (33); Iron (32); Copper (29)                                                                                                                                                                                      |
| <b>Most represented research approaches</b> | Field experiment (37); Guidance/extension (26); Greenhouse study (10); Lab study (6)                                                                                                                                                               |

### Key Evidence Message

The available knowledge does not identify a single micronutrient application strategy that is consistently preferable across crops, nutrients and production conditions.

The available knowledge shows that management choices are interdependent. A delivery method that is appropriate for one nutrient deficiency or soil condition may be ineffective in another situation, and the response to a product depends on when, where, and how it is applied. Specialized formulations and integrated products can alter nutrient uptake, root

growth, nodulation, or physiological response, but those changes do not necessarily translate into a consistent yield advantage.

The practical emphasis is therefore on matching the management strategy to a diagnosed deficiency and production context, rather than routinely adding micronutrients to a fertility program.

## Application route and placement

### Theme at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                                                                                    |
|---------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Theme focus</b>                          | Delivery of micronutrients through foliar, soil, seed, starter, in-furrow, banded, or near-seed application.                               |
| <b>Records</b>                              | 61                                                                                                                                         |
| <b>Knowledge Concepts</b>                   | Foliar micronutrient application; Soil-applied micronutrients; Seed treatment and seed priming; Starter fertilizer and near-seed placement |
| <b>Crop profile</b>                         | Corn (31); Soybean (26); Corn & Soybean (4)                                                                                                |
| <b>Most represented micronutrients</b>      | Zinc (41); Manganese (33); Boron (31); Iron (25); Copper (23)                                                                              |
| <b>Most represented research approaches</b> | Field experiment (28); Guidance/extension (23); Greenhouse study (6); Lab study (3)                                                        |

### Key Evidence Message

Foliar, soil, seed, starter, and near-seed routes serve different objectives.

Application route and placement determine where and when the nutrient becomes available to the crop. Foliar, soil-applied, seed, starter, in-furrow, and near-seed methods are not interchangeable. Their suitability depends on the treatment objective, nutrient mobility, timing of deficiency, and root-zone conditions.

Study 188 illustrates the value of matching placement to a clearly identified deficiency. In soybean grown on calcareous soils, in-furrow Fe-EDDHA increased yield of an IDC-susceptible variety where iron deficiency chlorosis was moderate to severe. Study 215 provides a contrasting result: neither soil-applied nor foliar micronutrients increased corn or soybean grain yield in any trial or year. Changing the delivery route therefore did not produce a response where field conditions were not responsive.

Foliar applications show the same need for targeting. Study 844 applied boron, copper, manganese, and zinc to soybean at V5-V6 and R2-R3. Fertilization sometimes increased leaf concentrations and often increased grain concentrations, but did not increase yield. Study 194 likewise found no significant soybean yield increase from a foliar zinc-manganese-boron

package in a high- versus low-input management comparison where visible nutrient deficiencies were minimal.

Taken together, the examples indicate that application route needs to be interpreted in relation to the identified nutrient deficiency and production conditions rather than treated as an independent predictor of response.

## Rate, timing, source, and formulation

### Theme at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                                          |
|---------------------------------------------|--------------------------------------------------------------------------------------------------|
| <b>Theme focus</b>                          | Selection of application rate, timing, nutrient source, chemical form, carrier, and formulation. |
| <b>Records</b>                              | 30                                                                                               |
| <b>Knowledge Concepts</b>                   | Application timing; Application rate; Fertilizer source and chemical form                        |
| <b>Crop profile</b>                         | Corn (20); Soybean (8); Corn & Soybean (2)                                                       |
| <b>Most represented micronutrients</b>      | Zinc (21); Manganese (13); Boron (11); Iron (11); Copper (10)                                    |
| <b>Most represented research approaches</b> | Field experiment (11); Guidance/extension (11); Lab study (4); Greenhouse study (4)              |

### Key Evidence Message

Rate, timing, source and formulation can influence nutrient availability, uptake and crop response, but their effects depend on the nutrient and production context.

How much nutrient is supplied, when it is applied, and the form in which it is delivered can all influence crop response. Study 1134 shows how application decisions can be tied to diagnosed risk. For corn in Ohio, the guidance indicates that soil pH generally needs to be above 6.6 and soil-test zinc below 4 ppm before a response to additional zinc would be expected, and identifies starter banding as an efficient placement where zinc is needed. Study 877 similarly indicates that soybean may respond to manganese where soil pH exceeds 7.4 and the DTPA soil manganese test is 10 ppm or less.

Study 946 demonstrates that source and placement can influence early crop performance. In southern Manitoba, starter fertilization increased early-season maize biomass and nutrient uptake, with the strongest early growth response where corn followed canola. However, Study 800, which summarizes 194 micronutrient trials in the tri-state region, reports that yield responses were rare and were limited to manganese in soybean.

Rate, timing, source, and formulation therefore matter within situations where a credible response is already expected. Fine-tuning the application does not by itself create a responsive field.

## Specialized products and nutrient carriers

### Theme at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                                                  |
|---------------------------------------------|----------------------------------------------------------------------------------------------------------|
| <b>Theme focus</b>                          | Use of chelated iron, nanofertilizers, nanoparticles, and organic or waste-derived nutrient carriers.    |
| <b>Records</b>                              | 26                                                                                                       |
| <b>Knowledge Concepts</b>                   | Chelated iron management; Nanofertilizers and nanoparticles; Organic and waste-derived nutrient carriers |
| <b>Crop profile</b>                         | Soybean (13); Corn (12); Corn & Soybean (1)                                                              |
| <b>Most represented micronutrients</b>      | Zinc (17); Iron (15); Copper (11); Manganese (10); Boron (7)                                             |
| <b>Most represented research approaches</b> | Field experiment (9); Guidance/extension (9); Greenhouse study (6); Lab study (2)                        |

### Key Evidence Message

Chelates, nanoparticles, organic carriers and recycled materials have been investigated as alternative delivery or biofortification approaches, but findings are product- and context-specific.

Specialized products include chelated micronutrients, nanofertilizers, nanoparticles, and organic or waste-derived nutrient carriers. These technologies may improve nutrient delivery or mineral enrichment, but their performance cannot be generalized across product categories. Much of the information for some specialized products also comes from greenhouse or laboratory settings, making transferability and safety important considerations.

Chelated iron provides the clearest field example in the representative evidence. Study 188 found that in-furrow Fe-EDDHA increased soybean yield under moderate to severe IDC and described it as a relatively low-cost strategy for mitigating the condition. Study 1177 similarly identifies ortho-ortho iron chelate as a management option for IDC and reports that available data generally support yield increases at recommended rates in affected areas.

The broader evidence remains more conditional. Study 724 reports no documented soybean grain-yield increase from zinc application across the cited Minnesota locations, while Study

877 limits manganese response expectations to soils meeting specific pH and soil-test conditions.

The synthesis indicates the need to evaluate specialized products according to the specific nutrient deficiency, product, field conditions, and strength of the supporting evidence, rather than assuming that a novel formulation is inherently more effective.

## Integrated and co-applied management

### Theme at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                                                                                              |
|---------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Theme focus</b>                          | Integration of micronutrients into multi-nutrient fertility programs and co-application with fertilizers, pesticides, adjuvants, or other compounds. |
| <b>Records</b>                              | 11                                                                                                                                                   |
| <b>Knowledge Concepts</b>                   | Integrated nutrient management; Product compatibility, adjuvants, and co-application                                                                 |
| <b>Crop profile</b>                         | Soybean (8); Corn (3)                                                                                                                                |
| <b>Most represented micronutrients</b>      | Iron (5); Zinc (4); Boron (3); Manganese (2); Molybdenum (2)                                                                                         |
| <b>Most represented research approaches</b> | Field experiment (7); Guidance/extension (2); Lab study (1); Greenhouse study (1)                                                                    |

### Key Evidence Message

Co-applying micronutrients with other inputs can alter crop response, but compatibility and causal attribution become more difficult as management packages become more complex.

Micronutrients are often applied as part of a broader fertility or crop-management program rather than as isolated treatments. Combining them with inoculants, fertilizers, pesticides, adjuvants, or other practices may change nutrient uptake, root development, nodulation, or crop performance. The trade-off is that multi-component treatments can make it difficult to determine which input caused the observed response.

Study 301 illustrates this issue in soybean. Greater root length density was observed where foliar boron was combined with two bacterial inoculants, but the combined treatment means that the contribution of boron cannot be separated from the effect of the inoculants.

Product compatibility can also be important. Study 893, conducted in Ontario, found that some manganese formulations tank-mixed with glyphosate caused crop injury or antagonized weed control under some conditions, and two combinations reduced soybean

yield relative to glyphosate alone. The study recommended sequential application of glyphosate and manganese. Study 1350 provides a different integrated example: raised beds increased soybean plant population and yield, while seed-applied Fe-EDDHA reduced IDC scores without significantly changing yield or biomass.

Integrated management can therefore alter crop performance, but compatibility, attribution, and the distinction between biological response and yield response need to remain explicit.

## Implications for micronutrient decisions

Once intervention is considered warranted, the available knowledge supports a targeted rather than prescriptive approach to implementation. Application route and placement determine where and when nutrients become available. Rate, timing, source, and formulation influence absorption and response. Specialized products may improve delivery under particular conditions. Integrated management can combine micronutrients with other inputs and practices.

Across these themes, however, no single strategy is consistently superior. In-furrow iron chelate can improve soybean yield where IDC is moderate to severe, while broad soil or foliar micronutrient programs frequently produce no yield response in non-deficient environments. Starter and side-banded fertilizers may improve early growth or nutrient uptake in particular situations, and some co-applied products can create antagonism or crop injury. Improvements in nutrient concentration, root growth, or deficiency scores do not necessarily establish a grain-yield advantage.

The practical implication is that management should follow diagnosis, not precede it. Taken together, the synthesis indicates that confidence in a management strategy is greatest when a credible micronutrient deficiency has been identified, the production conditions provide a plausible basis for response, and the rate, timing, source, placement and compatibility of the intervention are appropriate to that context.

The next Knowledge Cluster, Understanding Plant and Biological Processes, explains what happens after nutrients become available to the crop—how corn and soybean acquire, transport, regulate, and biologically respond to micronutrients.

# Understanding how crops respond to micronutrients

## Knowledge Cluster: Understanding Plant and Biological Processes

Understanding micronutrient management requires more than knowing whether a nutrient is present in soil or plant tissue. Crop response depends on what happens after nutrients become available: how they are absorbed, transported, partitioned, regulated, and used within the plant, and how roots, microorganisms, and symbiotic relationships influence those processes. The Understanding Plant and Biological Processes Knowledge Cluster contains 98 records organized into four themes: Nutrient Physiology, Uptake, and Partitioning (T14), Genetic, Genomic, and Ionomic Variation (T15), Root and Rhizosphere Processes (T16), and Microbial, Mycorrhizal, and Symbiotic Interactions (T17).

### Knowledge Cluster at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                                                                                                                                    |
|---------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Decision Pathway Component</b>           | Understanding how crops respond to micronutrients                                                                                                                                          |
| <b>What this cluster addresses</b>          | How corn and soybean acquire, transport, regulate, and partition micronutrients, and how genetic, root, rhizosphere, microbial, and symbiotic processes influence crop response.           |
| <b>Records</b>                              | 98                                                                                                                                                                                         |
| <b>Themes</b>                               | T14 Nutrient Physiology, Uptake, and Partitioning; T15 Genetic, Genomic, and Ionomic Variation; T16 Root and Rhizosphere Processes; T17 Microbial, Mycorrhizal, and Symbiotic Interactions |
| <b>Crop profile</b>                         | Corn (52); Soybean (44); Corn & Soybean (2)                                                                                                                                                |
| <b>Most represented micronutrients</b>      | Zinc (58); Iron (54); Manganese (41); Copper (32); Boron (30)                                                                                                                              |
| <b>Most represented research approaches</b> | Field experiment (46); Guidance/extension (19); Lab study (17); Greenhouse study (13)                                                                                                      |

### Key Evidence Message

Crop response to micronutrients depends on interacting physiological, genetic, root-zone and biological processes that influence nutrient acquisition, regulation and use.

These biological processes help explain why two crops grown under apparently similar nutrient conditions may not respond in the same way. Nutrients must first be acquired by roots, transported to active tissues, partitioned among plant organs, and regulated through physiological and genetic mechanisms. Root architecture and rhizosphere chemistry

influence access to nutrients, while microorganisms and symbiotic relationships can further alter nutrient acquisition and crop performance.

A key qualification runs through this Knowledge Cluster: biological response is not the same as agronomic benefit. A treatment can increase nutrient concentration, root growth, or physiological activity without producing a proportional increase in grain yield. Conversely, genetic or biological differences can change nutrient efficiency even under similar soil conditions.

## Nutrient physiology, uptake, and partitioning

### Theme at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                                                                              |
|---------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|
| <b>Theme focus</b>                          | Physiological and biochemical processes controlling micronutrient uptake, transport, accumulation, remobilization, and partitioning. |
| <b>Records</b>                              | 62                                                                                                                                   |
| <b>Knowledge Concepts</b>                   | Mechanistic nutrient physiology; Nutrient uptake, transport, accumulation, and partitioning                                          |
| <b>Crop profile</b>                         | Corn (38); Soybean (22); Corn & Soybean (2)                                                                                          |
| <b>Most represented micronutrients</b>      | Zinc (41); Iron (30); Manganese (27); Boron (21); Copper (21)                                                                        |
| <b>Most represented research approaches</b> | Field experiment (33); Lab study (12); Greenhouse study (8); Guidance/extension (8)                                                  |

### Key Evidence Message

Absorption, translocation, partitioning, and remobilization influence whether soil-derived or applied nutrients reach active tissues and grain.

Micronutrient availability in the soil is only the beginning of the process. Nutrients must be taken up, moved through the plant, accumulated in different tissues, and in some cases remobilized as the crop develops. Growth stage and management influence when micronutrients are acquired and where they ultimately accumulate.

Study 1051 shows how strongly uptake can vary over the season in maize. Maximum micronutrient accumulation occurred between V10 and V14, and most zinc and copper uptake occurred after flowering. Study 1062 provides a soybean comparison: producing about 3,500 kg/ha of grain required accumulation of 335 g Zn, 371 g Mn, 325 g B, 849 g Fe, and 63 g Cu per hectare. Supplemental fertility modestly increased biomass and yield, but did not alter nutrient partitioning or harvest index.

Management can further modify these patterns. Study 1185 found that plant density and nitrogen rate significantly influenced whole-plant nutrient contents in maize. Grain iron and zinc were primarily affected by nitrogen rate, while manganese and copper were influenced by the interaction between plant density and nitrogen. Study 1063 similarly found that maize rotation systems and nitrogen rates changed zinc, iron, magnesium, and copper uptake and internal efficiency.

These findings show that micronutrient uptake is dynamic across growth stages and management conditions. Greater nutrient accumulation is biologically meaningful, but does not by itself demonstrate greater yield or economic value.

## Genetic, genomic, and ionomic variation

### Theme at a Glance

| CHARACTERISTIC                       | SUMMARY                                                                                                                                      |
|--------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------|
| Theme focus                          | Genetic and genomic determinants of micronutrient efficiency, stress response, gene expression, and whole-plant or seed mineral composition. |
| Records                              | 46                                                                                                                                           |
| Knowledge Concepts                   | Genetic and genomic variation in micronutrient response; Gene expression under nutrient stress; Ionome variation                             |
| Crop profile                         | Soybean (27); Corn (18); Corn & Soybean (1)                                                                                                  |
| Most represented micronutrients      | Iron (31); Zinc (23); Manganese (16); Copper (14); Boron (12)                                                                                |
| Most represented research approaches | Field experiment (18); Guidance/extension (12); Lab study (10); Greenhouse study (4)                                                         |

### Key Evidence Message

Genetic and genomic variation can substantially influence iron efficiency, nutrient stress response, and seed mineral composition.

Crop genetics can strongly influence how micronutrients are acquired, regulated, and accumulated. This is particularly evident for soybean iron deficiency, where genotype can affect visible deficiency response as well as seed iron characteristics. Variation in the broader ionome also shows that mineral composition is not fixed within a crop species.

Study 1009 measured seed ionome variation across 90 soybean genotypes and found wide ranges in zinc, iron, copper, and manganese concentrations. Study 1164 identified a major quantitative trait locus for seed iron accumulation that explained 21.5% of the variation and

provided evidence of a possible genetic link between iron efficiency and iron accumulation in seed.

Study 1215 proposed seed iron concentration as an integrated measure of soybean resistance to iron deficiency and argued that it could be equivalent or superior to visual chlorosis scoring as a measure of iron efficiency. Study 755 found that zinc and manganese concentrations varied markedly by location among soybean genotypes differing in iron efficiency, while seed iron and manganese showed an inverse relationship.

The practical significance is that crop genotype can influence micronutrient response independently of soil supply. Breeding and phenotyping may provide avenues for developing or evaluating approaches to some micronutrient deficiencies, but their field performance requires further assessment. Genotype also interacts with environment and mineral composition, so genetic differences should not be interpreted in isolation.

## Root and rhizosphere processes

### Theme at a Glance

| CHARACTERISTIC                       | SUMMARY                                                                                  |
|--------------------------------------|------------------------------------------------------------------------------------------|
| Theme focus                          | Root traits and rhizosphere processes that modify nutrient acquisition and availability. |
| Records                              | 9                                                                                        |
| Knowledge Concepts                   | Rhizosphere acidification; Root traits and responses                                     |
| Crop profile                         | Corn (8); Soybean (1)                                                                    |
| Most represented micronutrients      | Manganese (4); Iron (3); Zinc (3); Copper (2); Boron (2)                                 |
| Most represented research approaches | Greenhouse study (5); Lab study (2); Field experiment (2)                                |

### Key Evidence Message

Root architecture and rhizosphere chemistry mediate access to poorly available nutrients.

A nutrient can be present in soil but still be difficult for the crop to acquire. Root growth, root architecture, rhizosheath formation, and changes in rhizosphere chemistry can alter nutrient access and uptake independently of the concentration measured in bulk soil.

Study 1061 illustrates the importance of root development under stress. Seed priming with iron or zinc plus manganese increased maize seed nutrient contents and, under low root-zone temperatures, significantly increased biomass and total root length. Study 1145 likewise

found that zinc and manganese treatments promoted maize growth and particularly root development under low root-zone temperature.

Rhizosphere chemistry can produce more complicated effects. Study 1159 examined a nitrification inhibitor intended to influence rhizosphere acidification in limed maize soil. Although the treatment promoted shoot biomass, it decreased shoot manganese concentration, and the study cautioned that using the inhibitor to improve phosphorus availability in high-pH soils could increase the likelihood of manganese deficiency. Study 112 provides another qualification: even under severe boron deficiency, maize did not show inhibited root growth or compensatory root-foraging behaviour.

Root and rhizosphere processes therefore help explain why nutrient availability measured in soil does not always correspond directly with plant uptake. Their effect depends on the nutrient, environmental conditions, and crop response.

## Microbial, mycorrhizal, and symbiotic interactions

### Theme at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                                                                                |
|---------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------|
| <b>Theme focus</b>                          | Microbial inoculants, mycorrhizae, rhizobia, nodulation, and biological interactions affecting nutrient availability or crop response. |
| <b>Records</b>                              | 9                                                                                                                                      |
| <b>Knowledge Concepts</b>                   | Microbial and mycorrhizal interactions; Nodulation and iron deficiency                                                                 |
| <b>Crop profile</b>                         | Soybean (6); Corn (3)                                                                                                                  |
| <b>Most represented micronutrients</b>      | Zinc (5); Iron (2); Manganese (2); Boron (1); Micronutrients (Mikrokomplex; composition not extracted) (1)                             |
| <b>Most represented research approaches</b> | Field experiment (6); Lab study (2); Greenhouse study (1)                                                                              |

### Key Evidence Message

Microbial and symbiotic interactions can modify nutrient acquisition, deficiency expression and root performance, but their agronomic effects are context-dependent.

Microorganisms and symbiotic relationships can modify how crops access and use micronutrients. Mycorrhizae, bacterial inoculants, rhizobia, and nodulation can influence nutrient acquisition, root performance, and deficiency expression. Their effects, however, depend on the organism, nutrient form, soil conditions, and compatibility with other treatments.

Study 256 demonstrates the relationship between nodulation and soybean iron deficiency chlorosis. In a controlled-environment assay, increasing calcium carbonate worsened IDC symptoms, while nodulation reduced symptoms across genotypes. Study 301 found greater soybean root length density when foliar boron was combined with two bacterial inoculants.

Field evidence provides an important qualification. Study 845 evaluated rhizobia inoculant, manganese fertilizer, and other inputs in soybean and found very little yield response to either inoculant or manganese in fields with corn-soybean rotation and limited manganese deficiency. Study 954 found that bacterial inoculation and foliar fertilization altered soybean seed mineral composition, including higher seed iron in inoculated treatments than in the control.

These findings show that biological interactions can alter nutrient status, roots, and symbiotic processes, but changes in those processes do not necessarily translate into a field-scale yield benefit.

## Implications for micronutrient decisions

Crop response to micronutrients emerges from an interconnected biological system. Uptake and partitioning determine when and where nutrients accumulate. Genetic variation influences nutrient efficiency, stress response, and seed mineral composition. Roots and rhizosphere chemistry affect access to poorly available nutrients. Microorganisms and symbiotic relationships can further modify nutrient acquisition and crop performance.

The representative evidence also shows that these processes are highly context dependent. Maize and soybean partition micronutrients differently across growth stages and plant tissues. Genotype can substantially alter mineral composition and iron-efficiency traits. Root growth and rhizosphere chemistry can change nutrient acquisition under cold or high-pH conditions, while nodulation and microbial inoculation can modify deficiency symptoms, root development, or seed nutrient concentration.

The critical decision point is that a biological response should not automatically be treated as evidence of agronomic value. Increased nutrient uptake, tissue concentration, root growth, or physiological activity may demonstrate that an intervention affected the crop, but those changes do not consistently produce corresponding grain-yield gains.

The central contribution of this Knowledge Cluster is explanatory. Changes in nutrient uptake, tissue concentration, gene expression, root development or microbial interactions can demonstrate that a micronutrient or management practice affected the crop, but they do not by themselves establish whether that response has practical value. Biological responses are therefore most useful for explaining how and why responses occur, why they vary among crops and environments, and why changes in nutrient status may or may not progress to agronomic outcomes.

The next Knowledge Cluster moves from mechanism to value. It examines whether micronutrient status and management translate into outcomes that matter for production

decisions, including crop growth and yield, nutritional quality, environmental effects and economic performance.

# Determining whether micronutrient intervention produces meaningful benefits

## Knowledge Cluster: Evaluating Outcomes, Value, and Safety

### Knowledge Cluster at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                                                                                                                                                                         |
|---------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Decision Pathway Component</b>           | Determining whether micronutrient intervention produces meaningful benefits                                                                                                                                                     |
| <b>What this cluster addresses</b>          | Agronomic, nutritional, environmental, safety, and economic outcomes associated with micronutrient status and management, including the consistency, direction, and risk of crop response.                                      |
| <b>Records</b>                              | 112                                                                                                                                                                                                                             |
| <b>Themes</b>                               | T18 Agronomic productivity and crop growth; T19 Nutritional quality and biofortification; T20 Soil, pest, and environmental outcomes; T21 Economic performance and profitability; T22 Response direction, consistency, and risk |
| <b>Crop profile</b>                         | Corn (63); Soybean (44); Corn & Soybean (5)                                                                                                                                                                                     |
| <b>Most represented micronutrients</b>      | Zinc (71); Manganese (55); Iron (54); Copper (43); Boron (38)                                                                                                                                                                   |
| <b>Most represented research approaches</b> | Field experiment (55); Guidance/extension (29); Greenhouse study (14); Lab study (12)                                                                                                                                           |

### Key Evidence Message

Micronutrient management can change nutrient status, physiology, biomass and grain mineral composition, while grain-yield responses are more variable and context-dependent.

This Knowledge Cluster distinguishes among several different forms of value. Agronomic outcomes include growth, biomass, and grain yield. Nutritional outcomes include grain or seed mineral concentration. Soil, pest, environmental, and safety outcomes extend the assessment beyond crop productivity. Economic outcomes depend ultimately on whether the benefit achieved is sufficient to justify the cost of intervention. These outcomes should not be treated as interchangeable.

The strongest pattern across the cluster is variability in response. Biological or nutritional changes can occur without a yield response, while positive yield effects are more credible where a deficiency or other responsive condition is present. A measurable effect of micronutrient management therefore does not necessarily establish agronomic or economic

value.

## Agronomic productivity and crop growth

### Theme at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                                                                                 |
|---------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|
| <b>Theme focus</b>                          | Effects on grain or seed yield, biomass, plant growth, development, and physiological performance.                                      |
| <b>Records</b>                              | 102                                                                                                                                     |
| <b>Knowledge Concepts</b>                   | Fertilizer response evaluation; Grain or seed yield response; Biomass and plant growth response; Physiological and biochemical response |
| <b>Crop profile</b>                         | Corn (60); Soybean (37); Corn & Soybean (5)                                                                                             |
| <b>Most represented micronutrients</b>      | Zinc (65); Manganese (50); Iron (47); Copper (40); Boron (37)                                                                           |
| <b>Most represented research approaches</b> | Field experiment (49); Guidance/extension (27); Greenhouse study (14); Lab study (11)                                                   |

### Key Evidence Message

Productivity outcomes occur at several levels, from early growth and biomass changes to grain yield, and improvements in nutrient status, physiology or biomass do not necessarily progress to field-scale yield gains.

Agronomic response can occur at several levels. Micronutrient status or management can affect nutrient accumulation, physiological performance, early crop growth, biomass, and final grain yield. These outcomes need to be distinguished because an improvement earlier in the response pathway does not necessarily result in greater harvested yield.

Study 1051 documented substantial micronutrient accumulation in modern maize, with maximum accumulation occurring between V10 and V14 and continued uptake of zinc and copper after flowering. Study 1185 similarly found that plant density and nitrogen rate significantly influenced whole-plant micronutrient contents. Together, these findings show that crop development and management can substantially alter micronutrient accumulation.

Yield outcomes were less consistent. Study 1062 found that supplemental fertility in soybean modestly increased biomass and yield by about 2%, without altering nutrient partitioning or harvest index. In contrast, Study 215 reported no corn or soybean grain-yield increase from either soil- or foliar-applied micronutrients in any trial or year.

For production decisions, the distinction is important: a change in nutrient uptake, physiology, or biomass provides evidence of crop response, but not necessarily evidence of a meaningful yield benefit.

## Nutritional quality and biofortification

### Theme at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                                                |
|---------------------------------------------|--------------------------------------------------------------------------------------------------------|
| <b>Theme focus</b>                          | Effects on grain or seed nutrient concentration, nutritional quality, and deliberate biofortification. |
| <b>Records</b>                              | 16                                                                                                     |
| <b>Knowledge Concepts</b>                   | Grain and seed nutritional quality and biofortification                                                |
| <b>Crop profile</b>                         | Corn (11); Soybean (5)                                                                                 |
| <b>Most represented micronutrients</b>      | Zinc (12); Manganese (10); Copper (9); Iron (8); Boron (2)                                             |
| <b>Most represented research approaches</b> | Field experiment (10); Greenhouse study (3); Lab study (2); Guidance/extension (1)                     |

### Key Evidence Message

Micronutrient management can change nutrient status, physiology, biomass and grain mineral composition, while grain-yield responses are more variable and context-dependent.

Not all micronutrient interventions are intended primarily to increase yield. Improving the mineral composition of grain or seed represents a distinct pathway of value. These changes may contribute to nutritional quality or a biofortification objective even where grain yield remains unchanged, although a change in mineral concentration alone does not establish nutritional benefit.

Study 1009 found substantial variation in the seed ionome among 90 soybean genotypes, including wide ranges in zinc, iron, copper, and manganese concentrations. This demonstrates the potential for genetic selection to influence seed mineral composition. Study 1136 shows that fertility management can also change mineral profiles: nitrogen fertilization decreased soybean seed zinc while significantly increasing copper and manganese.

Study 1392 provides a direct maize management example. Foliar zinc increased grain yield in both study years, while zinc and boron increased SPAD values and iron, copper, and molybdenum treatments increased total phenolic content and antioxidant capacity.

These findings show why grain and seed mineral composition needs to be evaluated as an outcome in its own right. Yield alone does not capture changes in mineral composition, and those changes should not be inferred from productivity outcomes.

## Soil, pest, and environmental outcomes

### Theme at a Glance

| CHARACTERISTIC                       | SUMMARY                                                                                             |
|--------------------------------------|-----------------------------------------------------------------------------------------------------|
| Theme focus                          | Effects on soil properties, pests or herbivory, and environmental safety.                           |
| Records                              | 12                                                                                                  |
| Knowledge Concepts                   | Soil property response; Pest and herbivory response; Environmental safety of micronutrient products |
| Crop profile                         | Soybean (7); Corn (5)                                                                               |
| Most represented micronutrients      | Zinc (7); Iron (7); Manganese (5); Boron (4); Copper (4)                                            |
| Most represented research approaches | Field experiment (7); Greenhouse study (2); Guidance/extension (2); Lab study (1)                   |

### Key Evidence Message

Soil, pest, environmental and safety outcomes are represented much less extensively than crop responses and therefore remain comparatively poorly characterized.

The consequences of micronutrient management can extend beyond crop growth and yield. Effects on soil properties, microorganisms, pests or herbivory, and environmental safety may also be relevant, particularly where products are used at high rates or where novel formulations and carriers are introduced. These outcomes, however, are less extensively represented in the knowledge base.

Study 1405 examined zinc fertilization in maize in relation to both crop growth and caterpillar herbivory. Zinc increased plant nutrient concentrations and greenhouse growth at intermediate rates, but early-season herbivore damage and caterpillar mass were unaffected, and zinc fertilization did not affect field grain yield. The biological, pest, and agronomic outcomes therefore differed within the same study.

Study 845 provides another field example. An omission trial in soybean evaluated rhizobia inoculant, gypsum, foliar manganese, insecticide, and fungicide. There was very little yield response to manganese or several of the other inputs because the fields had limited manganese deficiency and limited insect defoliation.

The comparatively limited coverage of this Theme means that soil, pest, environmental, and safety effects cannot simply be assumed from agronomic outcomes. They need to be considered and measured as separate endpoints.

## Economic performance and profitability

### Theme at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                              |
|---------------------------------------------|--------------------------------------------------------------------------------------|
| <b>Theme focus</b>                          | Costs, returns, profitability, and economic comparisons of micronutrient management. |
| <b>Records</b>                              | 5                                                                                    |
| <b>Knowledge Concepts</b>                   | Economic performance and profitability                                               |
| <b>Crop profile</b>                         | Soybean (5)                                                                          |
| <b>Most represented micronutrients</b>      | Zinc (3); Boron (2); Iron (2); Manganese (1); Cobalt (1); Molybdenum (1)             |
| <b>Most represented research approaches</b> | Field experiment (4); Guidance/extension (1)                                         |

### Key Evidence Message

Direct economic evidence is scarce. The available analyses show that agronomic response does not necessarily translate into profitability because economic performance also depends on the magnitude of the response, input and application costs, commodity value and production context.

Economic performance was one of the least developed areas of micronutrient knowledge. Only five records were coded to this theme. All five concerned soybean, and collectively they addressed zinc, boron, iron, manganese, cobalt and molybdenum. The small number of records and the limited coverage within individual micronutrients mean that the profitability of micronutrient management cannot be generalized across nutrients, products or production conditions.

The available records nevertheless established an important distinction between agronomic response and economic value. A treatment may increase yield or produce another measurable crop response without generating sufficient additional revenue to recover the costs of the product and its application. Conversely, the management strategy that maximizes yield is not necessarily the strategy that maximizes economic return.

Study 860 demonstrated this distinction directly. The Michigan field experiment evaluated soybean seeding rates and fertilizer treatments that included a fertilizer containing zinc along with nitrogen, phosphorus and sulfur. Net economic return was calculated using a partial budget that incorporated crop revenue and seed, fertilizer and application costs. Although

fertilizer treatments containing the multi-nutrient product increased grain yield by about 7%, economic outcomes differed among treatments. The study also found that maximum grain yield occurred at a higher seeding rate than maximum economic return.

The other economic analyses reinforce the importance of this distinction. Study 194 found that greater management intensity did not necessarily produce greater economic returns when the additional inputs failed to generate sufficient yield benefits. Study 583 concluded that several fertilizer strategies were not cost-effective under the conditions evaluated, while Study 1214 similarly found limited economic justification for in-season soybean fertilization under the production conditions considered. In contrast, Study 853 reported a favourable economic outcome for a treatment combining inoculation and foliar molybdenum. Together, these records show that economic outcomes can be positive or negative and depend on both crop response and the costs associated with obtaining that response.

The economic knowledge therefore remains too limited to support broad conclusions about the profitability of micronutrient management. What it does establish is that economic value cannot be inferred from biological or agronomic response alone. Decisions about micronutrient interventions require consideration of whether a response is likely, how large it is likely to be, what it costs to achieve, and whether the resulting production value is sufficient to offset those costs. The scarcity of direct economic analysis is itself an important knowledge gap, particularly if micronutrient recommendations are intended to support farm-level management decisions.

## Response direction, consistency, and risk

### Theme at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                                                                                                                                                             |
|---------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Theme focus</b>                          | Positive, negative, absent, inconsistent, or deficiency-dependent responses, including toxicity or overapplication risk.                                                                                            |
| <b>Records</b>                              | 63                                                                                                                                                                                                                  |
| <b>Knowledge Concepts</b>                   | Micronutrient toxicity or overapplication risk; Conditional response under deficiency; Predominantly no yield response; Inconsistent site-year response; Positive yield response; Negative yield or growth response |
| <b>Crop profile</b>                         | Corn (35); Soybean (25); Corn & Soybean (3)                                                                                                                                                                         |
| <b>Most represented micronutrients</b>      | Zinc (39); Manganese (32); Iron (24); Boron (24); Copper (23)                                                                                                                                                       |
| <b>Most represented research approaches</b> | Field experiment (31); Guidance/extension (19); Greenhouse study (9); Lab study (3)                                                                                                                                 |

### Key Evidence Message

Response variability is a consistent feature of the knowledge base: positive responses occur under some conditions, while no response, isolated response and occasional negative effects are also documented.

Variability is not simply noise in the knowledge base; it is itself an important finding. Positive, negative, absent, inconsistent, and deficiency-dependent responses reflect differences in baseline nutrient status, soils and environments, crop genotype, management, and whether a true deficiency exists.

Study 188 provides a clear deficiency-dependent response: in-furrow Fe-EDDHA increased yield of an IDC-susceptible soybean variety under moderate to severe iron deficiency chlorosis. Study 215 provides the contrasting pattern, with no corn or soybean grain-yield increase from soil- or foliar-applied micronutrients in any trial or year. Study 222 similarly reported no corn or soybean yield response to micronutrients across its trials.

The evidence also includes potential adverse effects. Study 851 found that broadcast boron, chlorine, manganese, and zinc generally did not increase soybean yield and that 2.2 kg B/ha sometimes reduced yield. Low manganese status represented an exception where a response could occur.

The practical lesson is therefore not simply that micronutrients sometimes work and sometimes do not. It is that positive responses are more readily interpretable where a documented deficiency or other responsive condition is present.

## Implications for micronutrient decisions

Determining whether a micronutrient intervention produces meaningful benefits requires first being clear about what constitutes a benefit. Nutrient uptake, physiological response, biomass, grain yield, nutritional quality, soil or pest effects, and profitability are different outcomes and should not be used interchangeably. The knowledge base is strongest for agronomic response testing, while economic, environmental, and safety outcomes are less extensively developed.

Across the representative evidence, changes in nutrient concentration or crop physiology often occurred without corresponding yield gains. Biofortification and seed mineral quality provide a separate pathway of value, and yield benefits can occur where a specific deficiency or responsive condition is present. At the same time, many multi-site field evaluations report no yield benefit, and unnecessary application can occasionally reduce yield.

The practical implication is that the value of micronutrient intervention is outcome-specific and conditional. The appropriate question is not simply whether an intervention produces a measurable response, but whether it produces the outcome that matters for the management objective. A biological change should not automatically be interpreted as a yield benefit;

improved nutritional quality should not be conflated with greater productivity; and an agronomic response does not establish profitability without considering its magnitude, consistency, and cost.

This distinction also changes how the knowledge base should be translated into recommendations. Knowing that a response can occur is not enough to determine whether intervention should be recommended in a particular field. The final Knowledge Cluster, Interpreting Evidence and Supporting Decisions, examines how the available information can be weighed, how uncertainty and transferability should be handled, and how it can be translated into field-specific production decisions and extension recommendations.

# Translating the knowledge into recommendations and decisions

## Knowledge Cluster: Interpreting Evidence and Supporting Decisions

The final stage of the applied pathway moves from understanding micronutrient knowledge to deciding how that knowledge should be used. The preceding knowledge clusters show that micronutrient need, availability, management, biological response, and outcomes are all conditional. Translating that information into recommendations therefore requires more than identifying whether a positive response has been reported. It requires consideration of how closely the available information matches the crop, soil, environment, management system, and decision being made.

The Interpreting Evidence and Supporting Decisions Knowledge Cluster contains 55 records organized into four themes: Extension Synthesis and Recommendation Principles (T23), Field-specific and Spatial Decision Support (T24), Diagnostic and Causal Uncertainty (T25), and Evidence Gaps and Transferability (T26).

### Knowledge Cluster at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                                                                                                                                                                                                      |
|---------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Decision Pathway Component</b>           | Translating knowledge into recommendations and decisions                                                                                                                                                                                                     |
| <b>What this cluster addresses</b>          | How micronutrient knowledge should be interpreted and translated into field-specific production decisions and extension recommendations, including local calibration, spatial variability, diagnostic and causal uncertainty, and limits on transferability. |
| <b>Records</b>                              | 55                                                                                                                                                                                                                                                           |
| <b>Themes</b>                               | T23 Extension synthesis and recommendation principles; T24 Field-specific and spatial decision support; T25 Diagnostic and causal uncertainty; T26 Evidence gaps and transferability                                                                         |
| <b>Crop profile</b>                         | Corn (27); Soybean (23); Corn & Soybean (5)                                                                                                                                                                                                                  |
| <b>Most represented micronutrients</b>      | Zinc (35); Boron (28); Manganese (28); Iron (26); Copper (23)                                                                                                                                                                                                |
| <b>Most represented research approaches</b> | Guidance/extension (28); Field experiment (23); Lab study (2); Observational/diagnostic/testing study (2)                                                                                                                                                    |

### Key Evidence Message

The evidence should be translated into field-specific decisions rather than broad blanket recommendations.

Across the cluster, a consistent decision principle is to begin with diagnosed need and interpret the available information within the local soil, crop, and production context. Evidence that helps explain a biological mechanism also needs to be distinguished from evidence that directly supports a field recommendation. Uncertainty is part of the available knowledge and should be retained rather than removed through assumptions.

For Ontario, field evidence generated under Ontario or sufficiently comparable soil, climatic and corn or soybean production systems provides the most directly application information for management decisions. Findings from non-local or mechanistic investigations can help explain why a response might occur, but they do not automatically provide a basis for recommending particular products, rates, thresholds, or expected yield responses under Ontario conditions.

## Extension synthesis and recommendation principles

### Theme at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                                                                          |
|---------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|
| <b>Theme focus</b>                          | Translation of knowledge into practical recommendations, including avoiding routine blanket use and prioritizing diagnosed need. |
| <b>Records</b>                              | 42                                                                                                                               |
| <b>Knowledge Concepts</b>                   | Extension recommendation synthesis; Avoidance of routine blanket micronutrient use                                               |
| <b>Crop profile</b>                         | Corn (22); Soybean (16); Corn & Soybean (4)                                                                                      |
| <b>Most represented micronutrients</b>      | Zinc (28); Boron (23); Manganese (23); Iron (21); Copper (20)                                                                    |
| <b>Most represented research approaches</b> | Guidance/extension (28); Field experiment (12); Observational/diagnostic/testing study (2)                                       |

### Key Evidence Message

Extension guidance generally discourages routine blanket use and recommends diagnosis, local calibration, and targeted treatment.

The extension and advisory information in the knowledge base provides an important bridge between experimental findings and production decisions. Overall, this guidance is more conservative than the range of products and treatments that have been evaluated. It emphasizes identifying a credible deficiency or response risk, interpreting soil and plant information in context, and selecting a treatment only where there is a defensible basis for expecting benefit.

Study 215 illustrates why blanket application is discouraged. Across corn and soybean trials, neither soil-applied nor foliar micronutrients increased grain yield in any trial or year. Study

194 reached a similar conclusion in soybean: no single additional input, including a foliar zinc-manganese-boron product, significantly increased yield where visible nutrient deficiencies were absent.

Recommendations also need to account for how diagnostic information and products are used. Study 805 found that soybean foliar manganese, iron, and zinc concentrations varied with time of day and that restricting sampling to after 10:00 a.m. reduced variation. Study 893, conducted in Ontario, found that some manganese formulations tank-mixed with glyphosate caused crop injury or antagonized weed control and recommended sequential application.

Together, these findings are consistent with an approach based on diagnosis, standardized interpretation, and product-specific management, rather than routine micronutrient supplementation.

## Field-specific and spatial decision support

### Theme at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                                              |
|---------------------------------------------|------------------------------------------------------------------------------------------------------|
| <b>Theme focus</b>                          | Use of field-specific risk, spatial variability, and on-farm data to tailor micronutrient decisions. |
| <b>Records</b>                              | 9                                                                                                    |
| <b>Knowledge Concepts</b>                   | Spatial field variability and on-farm data; Need for site-specific management                        |
| <b>Crop profile</b>                         | Corn & Soybean (4); Corn (3); Soybean (2)                                                            |
| <b>Most represented micronutrients</b>      | Boron (7); Manganese (7); Zinc (6); Copper (4); Iron (3)                                             |
| <b>Most represented research approaches</b> | Field experiment (5); Guidance/extension (4)                                                         |

### Key Evidence Message

Site-specific information can identify variation in micronutrient deficiency risk within or among fields, but risk indicators alone do not establish where treatment will improve crop outcomes.

Micronutrient risk is not necessarily uniform across a farm or within an individual field. Soil properties and other conditions associated with deficiency may be concentrated in particular areas. Field-specific assessment can identify differences in risk, while evidence of crop response is needed to judge whether treatment would provide value in those areas.

Study 1134 provides an example for zinc in corn: soil pH generally needs to be above 6.6 and soil-test zinc below 4 ppm before a response to additional zinc would be expected. Study 1160 similarly identifies particular soil settings associated with greater manganese-deficiency risk, including heavily weathered sandy soils, peat or organic soils above pH 6.0, and calcareous mineral soils at pH 6.5 or above.

The implication is that risk indicators and field-response information need to be considered together. Soil conditions can identify where a response is more plausible, but regional and on-farm response information helps determine whether those indicators translate into an agronomically meaningful response.

## Diagnostic and causal uncertainty

### Theme at a Glance

| CHARACTERISTIC                       | SUMMARY                                                                                                                     |
|--------------------------------------|-----------------------------------------------------------------------------------------------------------------------------|
| Theme focus                          | Limits of diagnostic prediction and difficulty attributing effects to individual micronutrients in multi-nutrient products. |
| Records                              | 11                                                                                                                          |
| Knowledge Concepts                   | Poor diagnostic prediction of yield response; Confounding in multi-nutrient products                                        |
| Crop profile                         | Corn (6); Soybean (4); Corn & Soybean (1)                                                                                   |
| Most represented micronutrients      | Zinc (8); Boron (7); Manganese (6); Copper (5); Iron (3)                                                                    |
| Most represented research approaches | Field experiment (6); Guidance/extension (5)                                                                                |

### Key Evidence Message

Diagnostic indicators and multi-nutrient products often cannot establish a clear causal link to yield, and this uncertainty should be retained.

One of the most important distinctions for interpreting micronutrient information is the difference between measuring nutrient status and demonstrating that a particular micronutrient caused a crop response. Soil and tissue tests can provide useful diagnostic information, but their relationship with crop response can be weak or context dependent.

Multi-nutrient products introduce additional uncertainty because a response cannot necessarily be attributed to one component.

Study 844 demonstrates this limitation directly. Across 42 soybean sites, foliar micronutrient application did not increase yield, and relationships between soil and tissue tests were poor or not significant. Study 851 likewise found that soil tests for several micronutrients did not predict soybean yield response across multi-site trials, even though some applications increased tissue nutrient concentrations.

Not all situations are equally uncertain. Study 188 provides a comparatively clear deficiency-treatment-response relationship: in soybean with moderate to severe iron deficiency chlorosis on calcareous soils, in-furrow Fe-EDDHA increased yield of a susceptible variety. In contrast, Study 222 found no corn or soybean yield response to soil or foliar micronutrients across its trials.

The appropriate response to uncertainty is therefore not to assume either that micronutrients work or that they do not. It is to retain uncertainty unless the relationship among deficiency, treatment, and response has been sufficiently supported by the available evidence.

## Evidence gaps and transferability

### Theme at a Glance

| CHARACTERISTIC                              | SUMMARY                                                                                                                           |
|---------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|
| <b>Theme focus</b>                          | Research uncertainty, missing knowledge, and limits on generalizing findings across soils, environments, and production contexts. |
| <b>Records</b>                              | 7                                                                                                                                 |
| <b>Knowledge Concepts</b>                   | Research uncertainty and evidence gaps; Transferability across soils and environments                                             |
| <b>Crop profile</b>                         | Corn (4); Soybean (3)                                                                                                             |
| <b>Most represented micronutrients</b>      | Iron (4); Zinc (3); Boron (2); Manganese (2); Copper (2)                                                                          |
| <b>Most represented research approaches</b> | Field experiment (4); Lab study (2); Observational/ diagnostic/testing study (1)                                                  |

### Key Evidence Message

Important gaps occur where existing knowledge cannot yet be connected confidently to a field decision, particularly because of limited local calibration, economic analysis, multi-site validation, long-term evidence or direct comparisons among management options.

The usefulness of existing knowledge depends partly on whether findings can be transferred across soils, environments, and production systems. Controlled-environment and mechanistic

investigations can provide important explanations of biological processes, but they do not automatically establish field recommendations. Similarly, thresholds and relationships developed in one region may require recalibration before they are used elsewhere.

Study 256 illustrates this distinction. A 21-day controlled-environment assay found that increasing calcium carbonate worsened soybean iron-deficiency symptoms while nodulation reduced them. The findings help explain the biology of IDC, but the controlled conditions do not by themselves establish a field-management recommendation. Study 1061 similarly found that iron or zinc-plus-manganese seed priming improved maize seedling biomass and root growth under low root-zone temperature and reported higher final grain yields in the field component, while noting that the mechanisms underlying the yield effect required further investigation.

Field information also raises questions about calibration and attribution. Study 982 found relationships between corn ear-leaf nutrient concentrations and biomass or grain yield and concluded that some published sufficiency ranges may warrant updating. Study 1350 found that raised beds increased soybean population and yield, while seed-applied Fe-EDDHA reduced IDC scores but did not significantly change yield or biomass.

These examples show why locally relevant, replicated field information is particularly important for recommendations. Where local calibration, economic analysis, long-term effects, or direct product comparisons are lacking, those limitations should remain visible rather than being bridged through assumptions.

## Implications for micronutrient decisions

Translating micronutrient knowledge into a production decision requires interpretation rather than simple application of individual findings. Across this Knowledge Cluster, the consistent principle is that evidence becomes more useful when it can be connected to a diagnosed need, relevant production conditions and field-response information. Soil and tissue measurements, experimental responses and mechanistic findings each contribute different information, but none automatically establishes that a particular intervention will provide value in a specific field.

Uncertainty is therefore part of the decision process rather than something that should be removed through assumptions. Diagnostic indicators do not always predict yield response, nutrient concentrations can change without corresponding agronomic benefit, and multi-nutrient products can make causal attribution difficult. Findings generated under controlled or substantially different production environments may explain biological processes without being directly transferable to Ontario management.

The synthesis therefore supports field-specific interpretation of evidence rather than universal micronutrient prescriptions. For Ontario, evidence generated under Ontario or sufficiently comparable production conditions provides the most directly applicable information, while

mechanistic and non-local evidence can help explain why responses occur and identify conditions that warrant further evaluation.

These principles complete the six-part applied pathway. The next section reconnects the six knowledge clusters to examine how diagnosis, production context, management, biological response, outcomes and evidence interpretation interact across the knowledge architecture.

## Integration across the pathway

The six knowledge clusters describe different parts of micronutrient decision-making, but they do not operate independently. Diagnosis, causal context, management, biological response, outcomes, and interpretation contribute different information to the same underlying problem: determining whether micronutrient intervention is warranted, what form it should take, and whether it produces a meaningful and sufficiently well-supported response.

The connectivity analyses provide another way of examining this knowledge architecture. Rather than showing how much information is available for individual topics, as Figures 2 and 3 do, Figures 4–6 examine relationships within the knowledge base. Figure 4 shows how the 26 themes are connected through records that address them together. Figure 5 steps back to examine connections among the six knowledge clusters. Figure 6 identifies themes that occupy particularly important connecting positions across the architecture. Together, the three analyses show not only what kinds of knowledge are available, but how different kinds of knowledge are brought together across the records in the systematic map.

This distinction matters for the decision pathway. The six knowledge clusters are useful for separating a complex problem into manageable decisions. Figures 4–6 show why those decisions need to be brought back together when the available knowledge is interpreted and used.

### The knowledge architecture is interconnected

Micronutrient information does not fall neatly into isolated areas of diagnosis, management, biology and outcomes. Records frequently address several of these areas together. The co-occurrence analysis examines these connections by asking which themes are addressed within the same records (figure 4). A connection between two themes means that at least some records considered both; stronger connections indicate that they were addressed together more frequently. The analysis therefore shows how different types of micronutrient knowledge are brought together in the available records. It does not show that one theme causes or influences another.

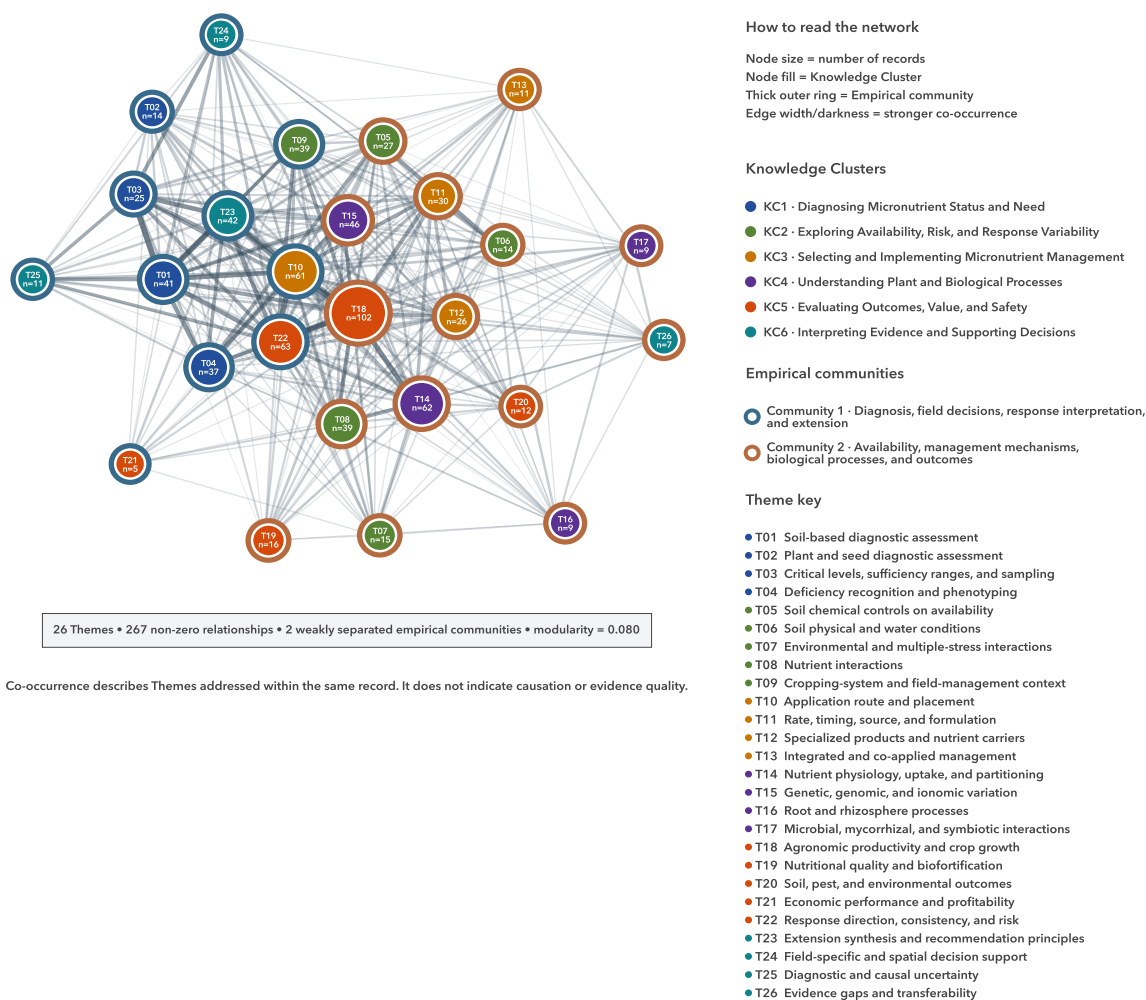


Figure 4. Connections among themes in the micronutrient knowledge base. Each circle represents a theme, with larger circles indicating themes supported by more records. Lines show where themes were addressed together, with stronger lines indicating closer connections. Colours identify the six knowledge clusters. The extensive connections across the network show that micronutrient knowledge is highly interconnected: diagnosis, factors affecting micronutrient availability and crop response, management, biological processes, outcomes and interpretation are often considered together rather than as separate areas of knowledge. Network analysis identified 293 theme-to-theme relationships. Community detection identified two weakly separated groups (modularity = 0.077), consistent with extensive connections across the knowledge architecture.

The pattern in Figure 4 shows extensive connections across the knowledge architecture. Themes concerned with diagnosis are addressed alongside information about critical levels and sampling, application decisions and extension recommendations. Application methods are frequently considered together with crop performance and the consistency of crop response. Agronomic productivity is connected with information about nutrient uptake and physiology as well as the interpretation of whether responses are meaningful and consistent.

In practical terms, the records often address more than one part of a micronutrient decision. Information about whether a crop may have a micronutrient problem is considered alongside information about how that problem is diagnosed or managed; information about an

intervention is considered alongside information about how the crop responds; and crop responses are considered alongside information used to judge whether those responses are meaningful. The six parts of the decision pathway can therefore be examined separately, but the available knowledge frequently connects them.

Consider diagnosis. A soil test value becomes more useful when it can be related to conditions affecting nutrient availability, crop response and locally relevant interpretation. Similarly, evidence that an application increased tissue nutrient concentration becomes more useful when it can be connected to crop performance and response consistency. The co-occurrence analysis shows where these types of information are addressed together in the records; the substantive findings in the preceding sections explain what those connections mean for micronutrient decisions.

The network also suggests two broad groupings of themes, but the separation between them is weak. More important for interpreting the synthesis is the extent of connection across those groupings. Diagnosis and decision-support topics are linked with management, biological processes and outcomes rather than forming separate bodies of knowledge.

## The knowledge clusters contribute different but complementary information

The same interconnectedness is apparent when the 26 themes are considered at the broader level of the six knowledge clusters. Figure 5, the Knowledge Cluster Connectivity Matrix, shows how often records contribute to more than one cluster and therefore where different parts of the decision pathway are most frequently addressed together.

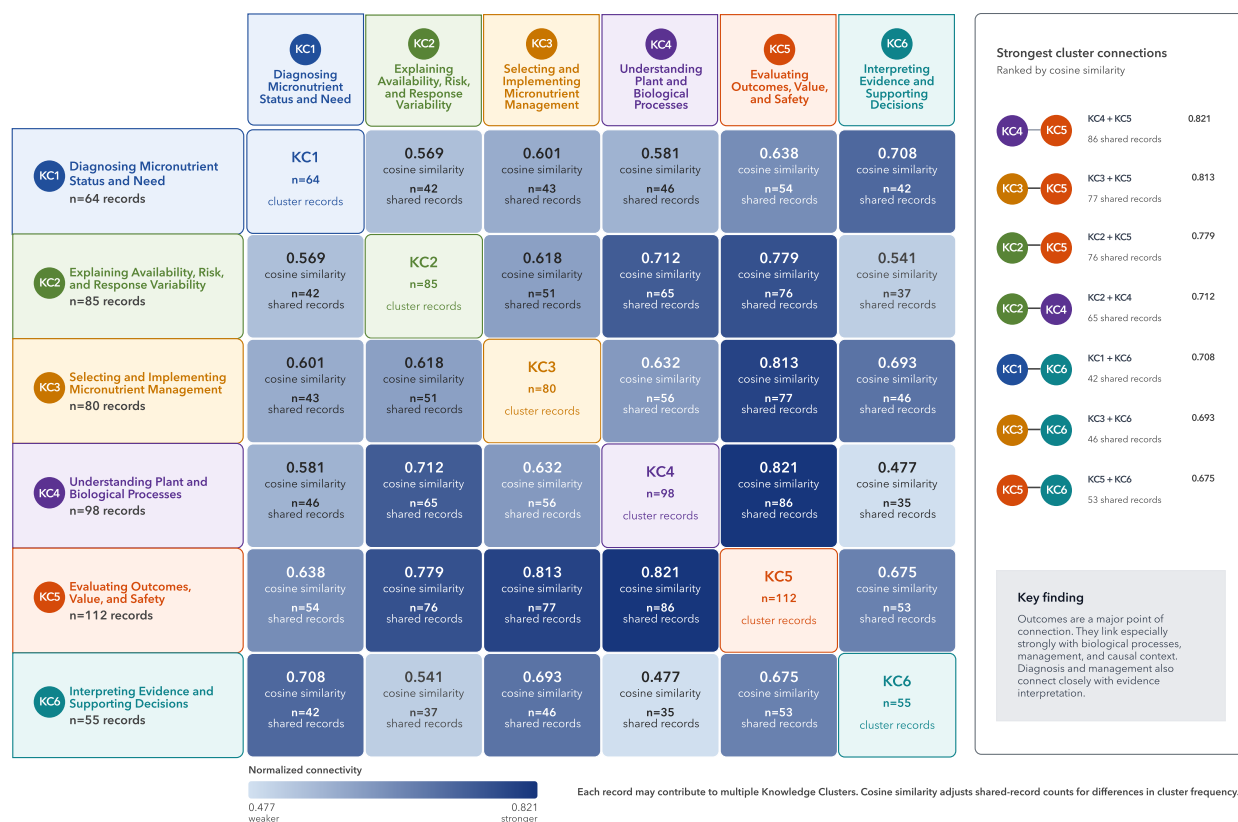


Figure 5. Connections among the six knowledge clusters. The matrix shows how often different parts of the micronutrient knowledge base are addressed together. Darker cells indicate stronger connections between knowledge clusters, while the diagonal shows the number of records contributing to each cluster. The strongest connections centre on evaluating outcomes, which is closely linked with biological processes, management, and the factors that influence micronutrient availability and crop response.

One of the clearest patterns centres on Evaluating Outcomes, Value, and Safety. This cluster shares 86 records with Understanding Plant and Biological Processes, 77 records with Selecting and Implementing Micronutrient Management, and 76 records with Explaining Availability, Risk, and Response Variability. In practical terms, information about whether an intervention produces a meaningful outcome is frequently addressed alongside information about how the nutrient was managed, the conditions affecting response, and what happened within the crop.

These relationships are consistent with the findings of the preceding Knowledge Cluster sections. Knowing that a crop responded is more informative when the response can be related to the intervention used, the conditions under which it occurred, and the biological processes that may help explain it. Conversely, information about nutrient availability, management or plant response has greater decision value when it can be connected with an outcome relevant to the objective of the intervention.

Another important pattern involves Interpreting Evidence and Supporting Decisions. This cluster shares 42 records with Diagnosing Micronutrient Status and Need, 46 records with Selecting and Implementing Micronutrient Management, and 53 records with Evaluating

Outcomes, Value, and Safety. This reinforces another conclusion from the individual Knowledge Cluster sections: information does not become a recommendation automatically. Diagnostic measurements require interpretation; treatment responses need to be considered in relation to their consistency and production context; and outcomes need to be judged against the objective of the intervention.

The connections among the clusters also help clarify how the decision pathway should be understood. The six areas are presented sequentially because this makes a complex body of knowledge easier to navigate, but they are not independent steps. In an actual micronutrient decision, information from one part of the pathway may change how another part is interpreted. An unexpected crop response may prompt reconsideration of the original diagnosis; field conditions may affect the appropriate management strategy; or uncertainty about the transferability of the evidence may limit a recommendation despite an apparently positive outcome.

### Some themes help connect the pathway

Not every theme occupies the same position within the knowledge architecture. Some occur across many records and connect with themes from several knowledge clusters, while others are more specialized. Figure 6 examines these differences using network centrality measures. Centrality does not indicate that one theme is more important, better supported, or more causally influential than another. Rather, it identifies themes that occupy particularly connected positions within the knowledge base.

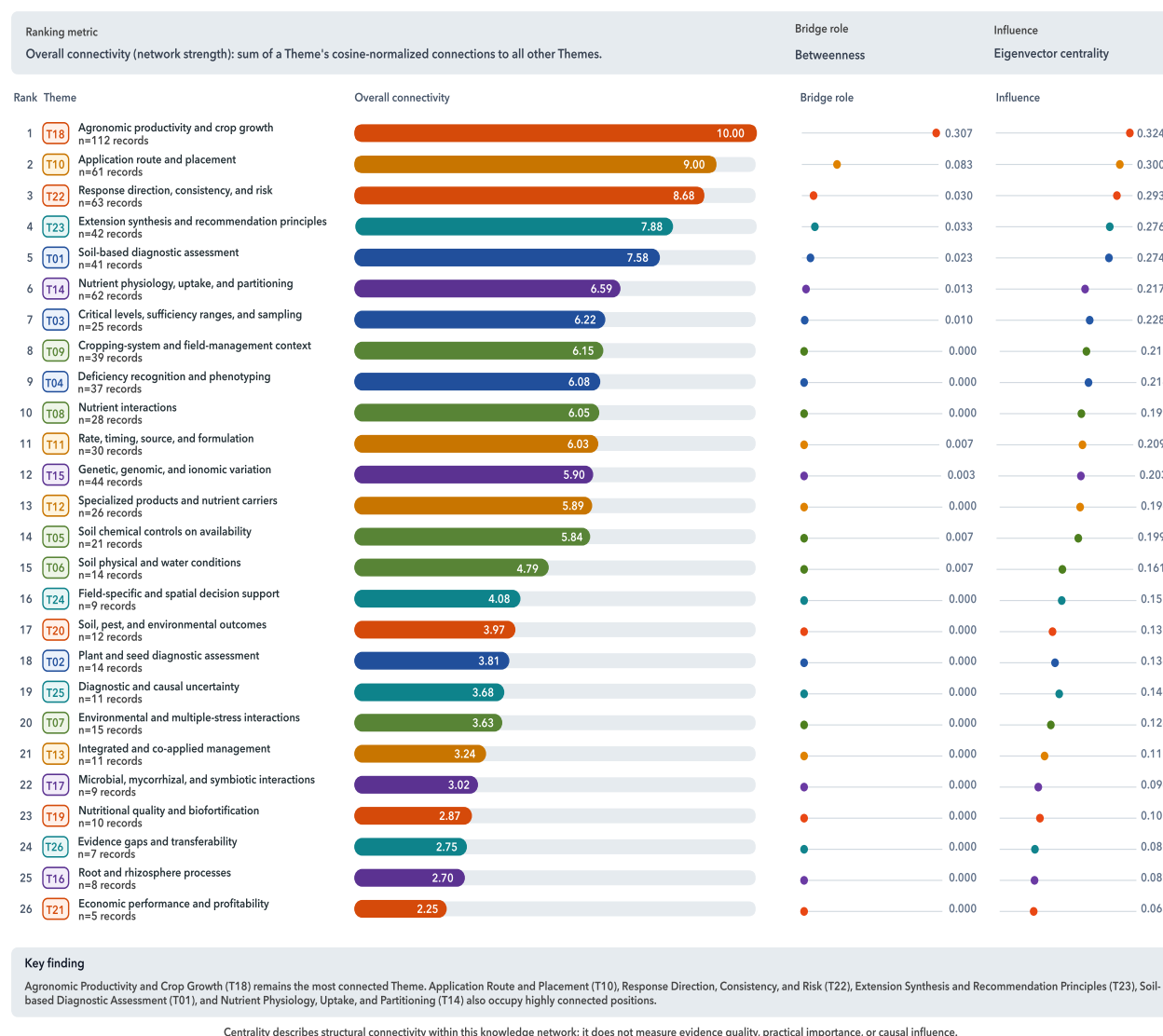


Figure 6. Themes that connect the micronutrient knowledge base. Themes are ranked according to how strongly they connect with other themes across the knowledge base. Agronomic Productivity and Crop Growth was the most highly connected theme, followed by Application Route and Placement and Response Direction, Consistency, and Risk. The ranking shows that a relatively small group of themes helps connect different parts of the micronutrient knowledge base, particularly crop outcomes, management decisions, diagnosis, biological processes, and interpretation of crop responses.

Several of the most connected themes correspond closely to key points in the applied pathway. Agronomic Productivity and Crop Growth (T18) occupies the most strongly connected position in the network and also has the strongest bridge role in the centrality analysis. Application Route and Placement (T10), Response Direction, Consistency, and Risk (T22), Extension Synthesis and Recommendation Principles (T23), Soil-based Diagnostic Assessment (T01), and Nutrient Physiology, Uptake, and Partitioning (T14) are also among the most highly connected themes.

The significance of this pattern is clearer when these themes are considered together. They represent questions such as:

1. Is there evidence of a micronutrient problem?
2. How should an intervention be delivered?
3. What happens to the nutrient and the crop?
4. Does the intervention affect crop performance?
5. Is that response consistent enough to be meaningful?
6. How should the information be translated into guidance?

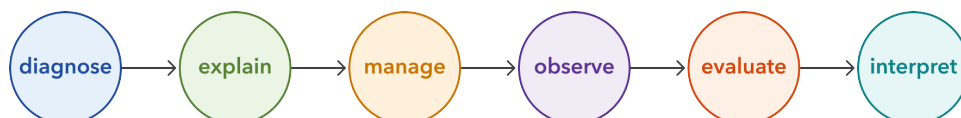
Figure 6 shows that themes corresponding to these decision questions occupy highly connected positions among the coded records. Agronomic Productivity and Crop Growth is particularly notable because many lines of inquiry ultimately intersect with crop performance. It co-occurs with themes concerning management, biological processes, diagnosis and response interpretation.

The more peripheral themes are equally informative. Several decision-relevant areas occupy comparatively peripheral positions in the network. Economic Performance and Profitability is the least connected Theme, while Field-specific and Spatial Decision Support, Soil, Pest, and Environmental Outcomes, Root and Rhizosphere Processes, Microbial, Mycorrhizal, and Symbiotic Interactions, and Evidence Gaps and Transferability also occupy relatively weakly connected positions. This does not mean they are less important to micronutrient decisions. Their peripheral positions show that these themes co-occur less often with other themes in the coded records.

For example, a substantial body of information about crop response has limited decision value if it is not connected to profitability. Similarly, knowledge about nutrient physiology may help explain response but does not by itself provide field-specific guidance. Figure 6 identifies where themes co-occur extensively and where potentially decision-relevant topics are less often represented together.

## From a pathway to an integrated decision framework

Taken together, the three connectivity analyses add an important dimension to the knowledge architecture. Figure 4 shows that the 26 themes are extensively interconnected. Figure 5 shows how those relationships extend across the six knowledge clusters. Figure 6 identifies the themes that most strongly connect different parts of the architecture. Together, the figures show how themes and clusters appear together across the records. The substantive findings in the six knowledge-cluster sections provide the further basis for interpreting these forms of information together. The resulting decision pathway is more than a sequence of steps:



Rather, these six elements form an integrated and potentially iterative decision framework. Diagnosis establishes whether there is credible evidence of a problem. Causal context helps determine whether a response is plausible. Management determines how intervention is implemented. Biological processes help explain the observed response. Outcomes establish whether the response produces something of value. Interpretation determines how confidently those findings can be applied. New information at any point can change how information from another part of the framework is understood.

The thematic findings also show why reliance on a single indicator can be problematic. A low soil or tissue value does not, on its own, establish that fertilizer will increase yield. A treatment-induced increase in nutrient uptake does not establish economic benefit. A positive response in one field does not establish that the same treatment should be recommended broadly. Each observation becomes more decision-relevant when it can be connected with information from other parts of the knowledge architecture.

The strongest micronutrient decisions therefore occur when multiple lines of information reinforce one another. Confidence is greater when a diagnosed need is consistent with the soil and production context; the management strategy is appropriate to the identified deficiency; the observed biological response is plausible; an outcome relevant to the management objective is demonstrated; and the supporting information is sufficiently consistent and transferable to the production setting.

Conversely, the framework helps make uncertainty visible. Confidence should remain lower where these connections are incomplete—for example, where nutrient status changes without an agronomic response, where a treatment response occurs without evidence of deficiency, where biological findings have not been demonstrated under field conditions, or where yield effects have not been connected with economic value.

The thematic synthesis supports considering diagnosis, production context, management, biological response, outcomes and evidence interpretation together when making micronutrient decisions; Figures 4–6 show how frequently these topics appear together in the records. The value of the knowledge architecture is not simply that it organizes the available information. It provides a way to understand how different forms of knowledge complement, qualify, and strengthen one another—and where missing connections create uncertainty in the decision process.

This integrated perspective provides the foundation for considering what the knowledge base means specifically for micronutrient management in Ontario. Section 10 brings together the major findings from across the six knowledge clusters and the connectivity analyses to identify what can be said with confidence, where management decisions remain conditional or uncertain, and where additional knowledge would most strengthen field-specific guidance.

## What this means for micronutrient management in Ontario

The knowledge base provides a substantial foundation for understanding micronutrient management in corn and soybean, but it does not support a simple conclusion that more micronutrient use will improve crop performance. Instead, the synthesis points toward a more targeted approach in which micronutrient decisions are based on diagnosed need, field conditions, appropriate management, expected outcomes, and the relevance and strength of the supporting information.

This distinction is particularly important for Ontario. The knowledge base was deliberately constructed to include records considered relevant to Ontario based on similarities in climate, soils and glaciation history, and corn and soybean production systems. Even within this selected body of information, however, the depth and applicability of knowledge vary substantially among micronutrients, management decisions, and production conditions. The implications for Ontario are therefore best understood as principles for strengthening decision-making, rather than as new nutrient recommendations or thresholds.

### Start with evidence of need

The clearest message across the synthesis is that micronutrient intervention should begin with a credible reason to expect a response. Soil testing, plant and tissue analysis, deficiency symptoms, critical levels, and other diagnostic approaches can all contribute useful information, but none consistently provides a complete answer on its own.

This is particularly important because nutrient status and fertilizer responsiveness are not equivalent. A soil or tissue test may indicate a relatively low nutrient concentration without establishing that fertilizer application will increase yield. Similarly, micronutrient application can increase tissue or grain nutrient concentrations without producing an agronomic response.

For Ontario production, the most defensible approach is therefore to combine diagnostic information with field history, soil and environmental conditions, crop observations, and locally relevant response information. Where several indicators point toward the same micronutrient deficiency, there is a stronger basis for considering intervention than where a decision rests on a single measurement or generalized threshold.

### Account for the conditions that make response more or less likely

The synthesis also shows why micronutrient response can be difficult to predict. Soil pH, carbonate conditions, texture, organic matter, drainage and moisture influence nutrient availability and root access. Temperature and other stresses can alter nutrient uptake and demand. Macronutrient supply and other inputs can interact with micronutrients. Rotation, plant population, field configuration, and other management practices can further influence measured response.

These relationships mean that a micronutrient treatment that performs well in one location cannot automatically be expected to perform similarly in another. The relevant question is not simply whether a product or practice has produced a positive response, but under what conditions that response occurred and whether those conditions resemble the Ontario field in which the intervention is being considered.

This conditionality also creates an opportunity for more precise management. Rather than treating an entire crop, region, or field as equally responsive, the knowledge architecture points toward identifying combinations of soil, crop, environmental, and management conditions associated with greater deficiency and response risk.

## Match management to the diagnosed deficiency

Where intervention is warranted, the knowledge base does not identify a single application strategy that is consistently superior. Foliar, soil, seed, starter, in-furrow, and other approaches serve different purposes, while rate, timing, source, formulation, and compatibility with other inputs can all influence performance.

The implication for Ontario is that management should follow diagnosis rather than precede it. Product selection and application practices should be matched to the nutrient deficiency, crop stage, soil conditions, and intended outcome. The presence of a micronutrient in a product or fertility program is not itself evidence that the crop requires it.

The same principle applies to specialized and multi-nutrient products. These products may affect nutrient status, roots, physiology, or crop performance, but multi-component formulations can make it difficult to determine which component produced the response. Product claims therefore need to be considered against independent, locally relevant information demonstrating that the intervention addresses an identified deficiency and produces an outcome of value.

## Be explicit about the outcome that matters

One of the most important contributions of the synthesis is the distinction among different kinds of crop response. Micronutrient management can affect nutrient uptake, tissue concentration, plant physiology, root development, biomass, grain yield, grain mineral composition, and other outcomes. These responses are related, but they are not interchangeable.

For most production decisions, a measurable biological response is not sufficient evidence of agronomic value. Increased tissue nutrient concentration, for example, demonstrates that nutrient status changed; it does not demonstrate that grain yield increased. Similarly, improved early growth or biomass does not necessarily persist through to harvest.

At the same time, grain yield is not the only potentially meaningful outcome. Changes in grain or seed mineral composition may be relevant where biofortification is the objective, although a measured change alone does not establish nutritional benefit. Environmental, soil,

and pest outcomes may also matter. The appropriate measure of success therefore depends on the purpose of the intervention.

Economic performance adds another important level, but it is one of the least developed parts of the knowledge base. Only five records were coded to the theme that focused on costs, returns, profitability or cost-effectiveness, and all concerned soybean. The available information nevertheless establishes an important principle: where the production objective is improved financial performance, a statistically or biologically measurable crop response must be large and consistent enough to justify the cost of the product and its application.

## Give greatest weight to locally relevant field information

Not all information in the knowledge base should carry equal weight in an Ontario production decision. Controlled-environment and mechanistic work can provide valuable explanations of nutrient uptake, genetic regulation, root processes, or stress responses. Such information can help explain why a response might occur, but it does not necessarily establish whether a particular treatment will produce a useful response under Ontario field conditions.

Similarly, diagnostic thresholds, sufficiency ranges, application rates, and recommendations developed elsewhere should not automatically be transferred to Ontario. Their usefulness depends on the comparability of soils, climate, cropping systems, analytical methods, and management conditions.

For Ontario recommendations and guidance, the most directly applicable basis comes from replicated field information generated in Ontario or under sufficiently comparable production conditions, supported where appropriate by mechanistic and controlled-environment information that helps explain the observed response.

This does not mean that findings from elsewhere are unimportant. They can identify potentially relevant relationships, management approaches, and emerging questions. The distinction is one of evidence use: information useful for understanding a micronutrient problem is not necessarily sufficient for prescribing how Ontario producers should manage it.

## Recognize that the knowledge is uneven

The synthesis shows that micronutrients and decision areas are not equally represented in the Ontario-relevant records. Zinc, iron and manganese have comparatively broad thematic coverage, while molybdenum, nickel, cobalt and chlorine/chloride have considerably less. Some decision areas are also represented in relatively few records. Economic performance and profitability is particularly limited, with only five records, while field-specific decision support, environmental outcomes, root and rhizosphere processes, microbial interactions and evidence gaps and transferability are also sparsely represented.

These gaps need to be interpreted carefully. Limited information is not evidence that a micronutrient, process, or outcome is unimportant. It means that the knowledge base provides less support for drawing conclusions about it.

The unevenness of the knowledge also suggests that future work should not simply seek to increase the volume of micronutrient information. Greater value would come from addressing the specific gaps that currently constrain decisions: stronger local calibration of diagnostic indicators, replicated multi-site field evaluations, clearer comparisons among products and application strategies, economic assessment, longer-term soil and environmental outcomes, and better understanding of the conditions that distinguish responsive from non-responsive fields.

## Toward more confident micronutrient decisions

The findings do not support either routine micronutrient supplementation or a conclusion that micronutrient intervention is generally unnecessary. Both would oversimplify a knowledge base characterized by conditional and variable responses.

Instead, the synthesis supports a more discriminating approach. Confidence in an intervention should be greater where:

- there is credible diagnostic evidence of a micronutrient deficiency;
- soil, environmental, crop, and management conditions provide a plausible explanation for that deficiency;
- the intervention is appropriate to the nutrient and production conditions;
- the expected biological response is consistent with the proposed management mechanism;
- the intervention produces an outcome that matters for the management objective;
- and the supporting information is sufficiently relevant, consistent, and transferable to the Ontario production setting.

Where these elements do not align, confidence in the intervention or recommendation should be lower. This may indicate a need for additional diagnosis, a greater risk that the crop will not respond, or insufficient knowledge to support a recommendation.

The practical contribution of the decision pathway is therefore not a new set of universal micronutrient prescriptions. Rather, it provides a framework for asking better questions before making a micronutrient decision: Is there a credible problem? What is causing it? What intervention fits those conditions? How should the crop respond? Did the response produce something of value? And is the supporting information strong and relevant enough to justify the decision?

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We gratefully acknowledge  
the project funders

