SUSTAINABLE STORAGE OF GRAINS
BY IMPLEMENTING A NOVEL PROTECTANT
AND A VERSATILE APPLICATION TECHNOLOGY

D1.3 Summary (manual) on resistance in Europe and its management

novIGRain

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1. Introduction

Protecting stored grain relies on a shrinking number of approved insecticides. Because the same few active substances are used repeatedly, stored product pests are becoming increasingly resistant to them. Globally, these insects are among the most difficult to control. They make up six of the top 30 most insecticide resistant arthropod species.

Despite this risk, systematic monitoring of resistance in Europe has been largely absent. A survey conducted during the NovIGRain project showed that data on pest resistance to the main chemical groups (phosphine, pyrethroids and organophosphates) are missing for 46% of European Union countries and 61% of all European countries.

As a result, pest control decisions in European grain stores are often made blindly. Operators frequently apply standard treatments without knowing if the local pest populations are already resistant. This leads to control failures, damaged grain and financial loss. It also makes the underlying problem worse, as exposing surviving insects to ineffective chemicals simply drives further resistance.

To address this, the NovIGRain project under Work Package 1 conducted systematic testing across several countries to measure actual resistance levels across Europe (Stejskal, 2025). This manual summarises those findings. It is written specifically for practitioners. It outlines which pests are resistant to which chemicals and provides guidelines on how to manage and prevent insecticide resistance in operational storage facilities.

2. Resistance Status by Active Substance

2.1. Phosphine

Phosphine remains the primary fumigant used for disinfesting stored grain globally, valued for its ability to penetrate deep into grain masses and eliminate pests across all life stages. However, because it is relied upon so heavily, resistance to phosphine is now the most widespread and severe resistance challenge facing the European grain storage sector.

To measure the true extent of this problem, the NovIGRain project assessed field strains of six key pest species collected from various storage facilities, including farms, cooperatives and large industrial elevators, across several European countries. Resistance was evaluated using the internationally recognised Detia Degesch Phosphine Tolerance Test Kit (DDPTTK). In this rapid diagnostic test, adult insects are exposed to a fixed concentration of 3000 ppm of phosphine gas. If the insects are not immobilised or knocked down within a strictly defined timeframe for their species, the population is confirmed as resistant.

The findings confirm that phosphine resistance is present across several major pest species across Europe:

- High risk species: The lesser grain borer (*Rhyzopertha dominica*) demonstrated the highest frequency of resistance, with 89% of tested strains proving resistant to phosphine. This was closely followed by the confused flour beetle (*Tribolium confusum*) at 75-80% and the rice weevil (*Sitophilus oryzae*) at 62%.

- Lower risk species: Resistance was notably lower, though still present, in the granary weevil (*Sitophilus granarius*) at 26% and the sawtoothed grain beetle (*Oryzaephilus surinamensis*) at 14%.
- Geographic spread: Resistant populations were not isolated to a single region. Phosphine resistance was confirmed in strains originating from the Czech Republic, France, Greece, Hungary, Italy and Spain.

These results demonstrate that operators can no longer assume phosphine will provide complete control, particularly when dealing with *R. dominica, T. confusum* or *S. oryzae*. Treating these resistant populations with standard doses of phosphine is highly likely to result in control failure and will only serve to strengthen the resistance within the surviving insect population.

2.2. Deltamethrin

Deltamethrin is a synthetic pyrethroid insecticide widely used across the storage sector. Valued for its fast knockdown effect and long residual activity, it is routinely applied to storage structures and sometimes directly to grain. Because it can provide ongoing protection long after the initial application, it is often viewed by operators as a reliable safeguard or a practical alternative where fumigation is difficult.

To determine if this confidence is still justified, the NovIGRain project evaluated the resistance of field collected pest strains to deltamethrin using a modified test method based on standard United Nations Food and Agriculture Organization (FAO) protocols. This process involves establishing a discriminatory dose on known susceptible laboratory strains, and then applying this baseline to field populations to identify which strains can survive what should be a lethal exposure.

The results from this testing phase highlight that while deltamethrin remains broadly effective against some pests, severe resistance has developed in others:

- High risk species: The lesser grain borer (*Rhyzopertha dominica*) showed significant resistance, with 65% of tested populations able to survive the discriminatory dose. The rice weevil (*Sitophilus oryzae*) also demonstrated a concerning level of resistance at approximately 35%.
- Low risk species: In contrast, the granary weevil (*Sitophilus granarius*) showed zero resistance among the strains tested, indicating that deltamethrin remains highly effective against this specific pest.
- Geographic spread: Similar to phosphine, deltamethrin resistance is not an isolated local issue. Resistant strains were identified across multiple countries, including the Czech Republic, France, Greece, Hungary, Italy and Spain.

These findings show that deltamethrin is not a universal fallback option. While it may still provide excellent control for certain species, relying on it to manage *R. dominica* or *S. oryzae* without prior testing is a high-risk strategy. Operators using deltamethrin to replace ineffective phosphine treatments may find they are simply substituting one failing chemical for another

2.3. Pirimphos-methyl

Pirimiphos-methyl is a systemic organophosphate insecticide heavily relied upon in the European storage sector. In addition to acting as a standard contact surface treatment, it possesses a slight fumigant action, allowing it to reach pests hidden within bulk grain masses. It is frequently used to manage a broad spectrum of beetles and moths in large-scale storage environments.

To evaluate current resistance levels against this active substance, the NovIGRain project assessed field-collected strains across multiple European countries. As with deltamethrin, testing was conducted using a modified FAO discriminatory dose method. A baseline lethal dose was established using known susceptible laboratory populations, which was then applied to the field strains to measure survival rates.

The findings from this testing indicate that while pirimiphos-methyl resistance is not yet as severe or widespread as phosphine resistance, significant vulnerabilities are emerging in specific pest species:

- Most affected species: The confused flour beetle (*Tribolium confusum*) demonstrated the highest frequency of resistance, with approximately 25% of tested populations able to survive the discriminatory dose. The rice weevil (*Sitophilus oryzae*) followed closely, showing resistance in 21% of tested strains.
- Low to zero resistance species: In contrast, the red flour beetle (*Tribolium castaneum*) showed zero resistance among the strains tested, indicating that pirimiphos-methyl remains a highly effective control measure for this specific species.
- Geographic spread: Resistant populations of *T. confusum* and *S. oryzae* were identified across several major agricultural regions, including France, Greece, Italy and Spain.

These results suggest that while pirimiphos-methyl remains a viable tool for many facilities, its efficacy can no longer be guaranteed across the board. Operators dealing with *T. confusum* or *S. oryzae* must be particularly cautious. As resistance to other chemical classes grows, the increased reliance on pirimiphos-methyl as a substitute will likely accelerate the resistance frequencies observed in these preliminary findings.

2.4. Multiple Resistance

While resistance to a single chemical limits control options, multiple resistance represents a fundamental threat to grain storage management. Multiple resistance occurs when a single insect population develops resistance to more than one active substance, often cutting off standard chemical rotation strategies. If a population is resistant to both a primary fumigant and a primary contact insecticide, facility operators are left with very few conventional tools to clear an infestation.

The NovIGRain testing has generated preliminary data showing that multiple resistance is already well established in European storage environments. Because resistance testing methods for deltamethrin and pirimiphos-methyl had to be developed before field screening could begin, testing across all substances is still ongoing. The figures presented here may be updated before final publication, but clear and concerning trends have already emerged.

Key findings to date include:

- High frequency: Depending on the species, between 19% and 40% of the resistant strains tested demonstrated multiple resistance, meaning they could survive exposure to at least two different active substances.
- Triple resistance: The most severe outcome, triple resistance to phosphine, deltamethrin and pirimiphos-methyl, has been confirmed in populations of the rice weevil (Sitophilus oryzae) and the confused flour beetle (*Tribolium confusum*).
- Low risk exceptions: Multiple resistance was almost entirely absent in the red flour beetle (*Tribolium castaneum*) and the sawtoothed grain beetle (*Oryzaephilus surinamensis*). This is largely because neither species showed resistance to pirimiphos-methyl in testing, even where their phosphine resistance was high.
- Geographic patterns: Current data indicates that multiple resistance is found most frequently in pest populations originating from southern Europe, particularly Greece and France. This is likely driven by the warmer climatic conditions and the historically higher intensity of insecticide use in these regions.

These preliminary findings indicate that some commonly relied upon control methods and rotation strategies may already be losing their effectiveness in the field.

3. Comparison of Europe to Global Resistance Patterns

When reviewing the high levels of resistance detailed in the previous sections, it is important to contextualise them against the wider international picture. A common assumption has been that severe insecticide resistance is primarily an issue for regions with warmer climates or different regulatory regimes, rather than a systemic European problem.

Recent global meta-analyses (e.g., Machuca-Mesa et al., 2024) demonstrate that phosphine resistance is a worldwide phenomenon, present in approximately 80% of internal feeder populations globally. Specifically, global resistance frequencies stand at around 94% for *R. dominica*, 84% for *S. oryzae*, and 28% for *S. granarius*.

The NovIGRain findings demonstrate that European resistance levels are closely aligned with these global patterns. Within the tested European strains, resistance in *R. dominica* was recorded at 89%, *S. oryzae* at 62%, and *S. granarius* at 26%.

This alignment confirms that Europe is not an exception to the global resistance crisis. The key difference is not the absence of resistance within the EU, but rather an historical lack of systematic documentation. Until the NovIGRain project, resistance data for phosphine, pyrethroids, and organophosphates were entirely missing for approximately 61% of European countries across the major target species.

The most severe data gaps relate to pyrethroids, with approximately 89% of potential resistance data points missing across Europe. Given that pyrethroids (such as deltamethrin) are among the most widely used structural treatments in European grain stores, this gap means that a significant portion of pest control decisions are currently being made blindly, without operators knowing if the products they are applying are still capable of delivering effective control.

4. What Resistance Means for Pest Control in Practice

The resistance data collected during the NovIGRain project is not just a scientific exercise; it has immediate, commercial implications for how grain is managed and protected across Europe. The high percentages of missing data and the confirmed presence of severe resistance mean that historical approaches to pest control are no longer viable.

For practitioner involved in grain storage industry, the project findings point to six major operational shifts:

1. Phosphine can no longer be assumed to work reliably

For decades, phosphine has been the default intervention for infested grain. However, the data shows that for key species, specifically *R. dominica, T. confusum*, and *S. oryzae*, standard fumigation may no longer be effective in many European facilities. Applying a standard dose of phosphine to a highly resistant population will not only fail to clear the infestation, but it will also actively select for the most resistant individuals, rapidly worsening the problem for future seasons.

2. Deltamethrin is not a universal fallback

A common industry response to phosphine failure is to switch to a pyrethroid structural or grain treatment, such as deltamethrin. The NovIGRain findings prove this is a high-risk strategy. Resistance to deltamethrin in *R. dominica* is already severe, and it is steadily increasing in *S. oryzae*. Relying heavily on deltamethrin as a direct substitute for phosphine simply replicates the original problem, placing immense selection pressure on a single chemical class.

3. Multiple resistance is rapidly narrowing the toolkit

The confirmation of multiple resistance, particularly triple resistance to phosphine, deltamethrin, and pirimiphos-methyl, is the most critical warning sign for the sector. Where pest populations have developed resistance to both primary fumigants and primary contact insecticides, operators are left with very few conventional, fast acting tools. Once a facility harbours a multiply resistant population, clearing an infestation becomes significantly more difficult and expensive.

4. Pyrethroid resistance is likely underestimated

The massive data gaps identified in the project, particularly regarding pyrethroids, represent a hidden threat. Because systematic resistance testing has been so sparse, especially across northern and eastern Europe, many facility managers are operating blindly. Operators routinely applying deltamethrin or similar pyrethroids may currently be managing highly resistant populations without realising that the chemical is no longer doing the heavy lifting in their pest control programmes.

5. Facility type and local geography matter

There is no longer a 'one size fits all' blueprint for European grain protection. The NovIGRain data indicates that resistance pressure differs significantly depending on the local

environment. Warmer southern European regions (such as Greece and Spain) show different resistance profiles compared to cooler northern climates. Similarly, resistance pressures vary between large industrial elevators, cooperative farms, and processing mills. Blanket treatments applied without knowledge of the local pest species and their specific resistance status are highly inefficient.

6. Juvenoid protectants may offer a necessary, complementary solution

Because conventional chemical options are shrinking, the sector requires alternative modes of action, including juvenoid grain protectants. Unlike traditional neurotoxic insecticides or fumigants, juvenoids act on the insect's endocrine system, preventing larvae from developing into reproducing adults. Crucially, because they employ a completely different mode of action, they may remain effective against populations that are already highly resistant to phosphine and pyrethroids.

Recent NovIGRain semi-field experiments compared how susceptible laboratory strains and resistant field strains reacted to new larvicide developed in NovIGRain project, a product using S-methoprene as its active ingredient. The results showed no consistent differences in population development between the two groups. Put simply, there was no evidence to suggest that the larvicide performs worse against populations that are already resistant to fumigants or liquid insecticides. While the scale and duration of the study limit broader conclusions about potential cross resistance, the lack of reduced susceptibility in resistant strains is an encouraging finding. This suggests that S-methoprene has potential as a complementary component in integrated pest management (IPM) programmes. By limiting insect population development, its application can directly support wider resistance management strategies in stored product protection.

5. Practical Resistance Management Recommendations

Effectively managing grain in the context of rising insecticide resistance requires a strategic shift. IPM provides the necessary framework, combining preventive, monitoring, physical, and chemical measures to reduce pest risk and slow the development of resistance. The following recommendations outline the core practices necessary to protect grain and preserve the efficacy of available control methods.

1. Testing and Sampling

Accurate decision making relies on accurate data. Applying chemical treatments without knowing the resistance status of the pest population significantly increases the risk of control failure.

- **Test before treating**: Where possible, utilise rapid resistance testing kits before selecting an active substance.
- **Sample correctly**: Follow established protocols for grain sampling to accurately identify pest presence. For full guidance, consult the NovIGRain Sampling Manual (Stejskal et al., 2023).

- **Identify the species**: Resistance profiles vary significantly between species. Identifying the specific pest is critical before choosing a product.

2. Monitoring and Inspection

Monitoring is the foundation of early intervention. It involves tracking both pest populations and environmental conditions within the grain store.

- **Combine visual checks and traps**: Conduct regular visual inspections alongside the use of pheromone traps and sticky boards to detect early signs of infestation.
- **Monitor temperature**: Track grain temperature continuously. Insect activity increases with warmth. Most chemical treatments, including fumigants, are only effective against active insects and are typically ineffective at temperatures below 10 °C.
- **Beware the 'frozen problem'**: Pests may become dormant during cooling, only to reactivate when temperatures rise during transport. This underscores the need for thorough cleaning and early treatment before temperatures fall.
- **Verify treatment efficacy**: Conduct routine post-treatment mortality assessments. Any unexpected insect survival should be regarded as an early indicator of emerging resistance and investigated immediately.
- **Report control failures**: Operators should establish a formal mechanism for reporting suspected control failures to national or European resistance monitoring networks. This generates valuable data that benefits the entire sector.
- **Document everything**: Record all trap catches, visual observations, and applied treatments (product, dose, date, and outcome) to track trends and evaluate effectiveness.

3. Preventive and Mechanical Measures

Reducing the initial pest pressure means you can use fewer chemical treatments, which in turn slows down the development of resistance.

- **Hygiene**: Thoroughly clean storage facilities before intake, removing all old grain, dust, and insect residues.
- **Structural integrity**: Seal cracks, gaps, and entry points to minimise hiding places and external reinfestation.
- **Moisture management:** Maintain grain moisture below safe threshold levels. Strict moisture control limits insect development, has a dramatic suppressive effect on mites and moulds, and contributes heavily to reducing the frequency of chemical interventions.
- **Grain cooling**: Actively manage ventilation to lower grain temperature below 15 °C. This slows insect development and metabolic activity, suppressing population growth.
- **Non chemical alternatives:** Because they do not rely on neurotoxic or fumigant modes of action, physical methods remain fully effective against multiply resistant populations. Where possible, utilise controlled or modified atmospheres (high carbon dioxide, low oxygen, or high nitrogen), hermetic storage systems, heat treatment of empty mills, and inert dusts beyond basic diatomaceous earth applications.

4. Chemical Measures and Product Rotation

When chemical intervention is necessary, it must be applied strategically to manage resistance.

- **Rotate active substances**: Never repeatedly apply the same active substance or mode of action. Rotate between fumigants (e.g., phosphine), pyrethroids (e.g., deltamethrin), organophosphates (e.g., pirimiphos-methyl), and physical protectants like diatomaceous earth.
- **Consider juvenoids**: Once fully authorised as a Plant Protection Product in your region, incorporate S-methoprene based products into your strategy. As a larvicide with a different mode of action, it is a valuable tool against populations resistant to adulticides.
- **Use the correct dose**: Always apply the authorised dose. Increasing the dose in response to poor control accelerates resistance and creates food safety risks.
- **Match the treatment to the facility**: Select formulations (e.g., emulsifiable concentrates, cold nebulisation, fumigants) appropriate for your specific storage infrastructure and consult local specialists regarding the correct application equipment.

5. Optimising Fumigation Quality

Resistance development is often driven less by the choice of fumigant than by the poor quality of its application. Exposing insects to sublethal doses actively selects for resistant individuals.

- **Ensure gas tightness**: Verify the complete hermetic sealing of any structure prior to fumigation.
- **Maintain concentration and time**: Monitor phosphine concentrations throughout the entire exposure period to ensure the correct concentration over time product is achieved.
- **Adhere to exposure periods**: Strictly follow the full label recommended exposure time, and ensure this period is adequately extended when operating at lower temperatures.

6. Training and Compliance

The safe and effective use of grain protectants is heavily regulated.

- **Ensure certification**: Operators must hold the appropriate, up-to-date pesticide applicator licences for the specific formulations they are using.
- **Specialised fumigant training**: Fumigants like phosphine are highly toxic and require advanced, specific certification covering gas tight sealing, gas monitoring, and the use of respiratory protective equipment.

7. Export and Complex Scenarios

- **Export requirements**: For short term storage prior to export, treatments must align with the specific requirements of the customer and the importing country.
- **Consult experts for multiple resistance**: If multiple resistance is suspected, standard treatment guidelines may be insufficient. Operators should urgently consult with local pest management experts to design a tailored control strategy.

6. Gaps and Limitations

While the NovIGRain project has provided critical new data on European resistance patterns, acknowledging the current gaps in the research is essential for informed decision making. These limitations highlight areas where further study and industry vigilance are required.

1. Nature of Resistance Testing

A significant limitation relates to the testing methodology itself. The DDPTTK phosphine test and FAO discriminating dose assays are qualitative tests that record whether an insect survived or did not survive. They detect the presence of resistance but do not quantify its magnitude, meaning they cannot distinguish between populations with slightly elevated tolerance and those with extreme resistance. Furthermore, the data are purely phenotypic. No specific genetic or molecular mechanisms were characterised, such as mutations in the *dld* gene for phosphine, *kdr* type mutations for pyrethroids, or metabolic detoxification mechanisms. This restricts the ability to predict cross resistance patterns or deploy rapid molecular monitoring.

2. Constrained Scope of Species and Life Stages

The study evaluated six primary pest species, three active substances, and a single life stage, the adult insect. Several important secondary pests at the European level were not included, such as the Indian meal moth (*Plodia interpunctella*), species of the genus *Ephestia* spp., *Cryptolestes* spp*., Trogoderma* spp., and mites (*Acarus* spp.). Additionally, larval and other developmental stages were not examined. Including a broader range of taxa and life stages in future research would improve the general applicability of these findings across all stored product pest systems.

3. Sampling Bias and Geographic Coverage

Although the project sampled across multiple European nations, the geographic distribution is uneven, with the Czech Republic being the most heavily represented. Reported resistance frequencies are sometimes based on relatively small numbers of populations for individual species and countries, and confidence intervals are not presented. Furthermore, only accessible and cooperating facilities were included in the study, which may theoretically introduce a certain degree of selection bias.

4. Preliminary Data and Pyrethroid Gaps

The figures regarding multiple resistance in Section 2.4 are preliminary. Because testing methodologies had to be finalised before full screening could begin, laboratory assays are still ongoing, with final data destined for a peer reviewed journal article. Alongside this, resistance data for pyrethroids remains the most incomplete across Europe. Despite pyrethroids being heavily utilised, an estimated 89% of potential historical data points are missing, making this the chemical class most in need of urgent monitoring.

5. Assessment Timeframe and Causation

The analyses are based on approximately five years of data collection, representing a medium-term assessment rather than a truly long-term monitoring programme. Because the

actual history of pesticide use at individual facilities was largely inferred, the relative contributions of climatic conditions versus insecticide use intensity cannot be clearly separated, particularly in southern European regions. However, the observed resistance frequencies are generally consistent with global scientific literature, supporting the overall credibility and biological relevance of the results.

6. Limitations of S-methoprene Trials

While laboratory results confirm that S-methoprene functions via a different mode of action, the semi-field trials evaluating its efficacy against specific resistant strains remain preliminary. The scale and duration of these initial trials were limited, meaning they do not yet provide a fully conclusive dataset regarding long-term efficacy or potential cross resistance mechanisms in commercial environments.

7. Future Tools and Ongoing Monitoring

To address these complexities, a decision support tool for resistance informed pesticide selection is a subsequent NovIGRain output that is made openly available for practitioners to use.

7. References

Stejskal, V. (2025). *D1.1.-Report on the resistance assessment and research for all common active substances*.

Stejskal, V., Aulicky R, & Vendl T. (2023). *Detection of Resistance in Storage Pests: Sampling, Preparation, and Sending of Samples for Resistance Analysis*.