Australian Government
Department of Agriculture and Water Resources

cebra
Centre of Excellence for Biosecurity Risk Analysis

Ministry for Primary Industries
Manatū Ahu Matua

CEBRA Report Cover Page

Title, ID, & Output #	*Compliance and risk based sampling for horticulture exports 1501E Output 7*		
Project Type	*Standard*		
Project Sponsor	*Plant Export Operations Branch*	**DAWR Project Leader/s**	*Russell Cant and Julia Lenton*
CEBRA Project Leader	*Andrew Robinson*	**NZ MPI Project Leader/s**	*N/A*
Project Objectives	*To recommend sampling methodologies that can be applied to consignments of mixed goods (and small consignments) to issue phytosanitary certification with a 95% level of confidence that there is less than 0.5% level of non-compliance with importing country requirements (potentially using historical compliance data).* *Recommendations as to the feasibility of using compliance data captured using the Plant Export Management System (PEMS) to implement compliance-based sampling.*		
Outputs	***Part A: Sampling Mixed consignments*** *The current policy of allowing the exporter a choice of 600 units or 2% inspection does not satisfy Australia's obligations under ISPM 31.* *Inspection of a simple random sample of 600 units from a mixed consignment does satisfy Australia's obligations under ISPM 31, provided that if contamination is detected the whole consignment is rejected.* *Stratification of a mixed consignment into risk classes (e.g., fruit fly hosts, root products, leafy greens), splitting a 600-unit sample between the strata proportional to stratum volume, rounding fractions up, and inspecting a simple random sample from each stratum to a total of at least 600 units, is a reasonable device to focus attention on the pathways that represent a higher risk to Australia's trading partners.* *Operational recommendations regarding the implementation strategy and impacts of the recommendations are presented, including the role of PEMS.* ***Part B: Compliance- Based Sampling*** *Compliance-based sampling is not possible with the current systems, as it would require the collection of an unprecedented level of detail from each consignment. In addition, it would be necessary to assume inspection history was continuous within supplier and region, from consignment to consignment when in practice this varies greatly.*		

CEBRA Workplan Budget	**Year 2015-16**			
	$25,000			

Project Changes	*Nil*
Research Outcomes	Part A • Refining the process at inspection for mixed consignments will: o Provide clearer direction for the inspectorate; o ensure Australia continues to meet international standards and obligations; o provide consistency for inspectors and clients Part B • The report has highlighted the complex and practical implications of compliance based sampling. It is clear this option is not viable.
Recommendations	1. Sampling by clusters of units will not achieve nominal sensitivity when contamination is clustered. If it is possible that the regulated pests of concern occur in a clustered pattern within the consignment then the inspectors should take every reasonable pain to ensure that the sampling is not clustered. This prescription may be more important for some commodities than others. 2. Where previously a choice between inspection of a 600-unit or a 2% sample had been offered to the exporter for exported plant products, the department now should

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	Report published	Date:

	require a 600-unit random sample. If the consignment size is known then a smaller sample size may be possible, see Figure 4.2. Furthermore, the sample should be taken as a simple random sample to the best of the inspector's ability. 3. For smaller consignment sizes, say 2000 or fewer units, the nominal sensitivity can be achieved with fewer than 600 units of inspection as long as the number of inspection units in the consignment is known. PEMS should compute and report the needed sample size to the inspector, with a simple rule of thumb applied as a backup, such as sample all units if the total number of units $N \leq 450$; 450 if $450 < N < 1000$; and 600 if $N > 1000$. 4. Communication between inspectors is paramount for ongoing training, developing culture, and sharing information about risky pathways. The department should facilitate communication between inspectors by some means, including but not limited to an official network along the lines of IBIS. 5. Use PEMS to provide automated feedback to pathway managers and inspectors about interception records and inspection patterns. This feedback could be graphical on a home-page, with click-through links to inspection and interception counts by region, supplier, or product, and hyperlinks to local issues of note. 6. Inspection data are vital for risk-based management of biosecurity pathways. The department should try to develop multilateral arrangements for sharing appropriate inspection data with trusted trading partners, or develop simple approximations using reported inspection results and information about the import inspection frequency of the importer. Knowing what shipments failed or required treatment would also provide useful feedback to producers and others associated with the pathway. 7. That mixed consignments have the 600-unit random sample split proportionately by volume between the lines, rounding fractional samples up, and a simple random sample be taken within each line to the best of the inspector's ability. 8. Use PEMS to monitor the sampling effort devoted to different products, and directing inspection efforts specifically or generally to ensure that reasonably up-to-date information on apparently low-risk products is maintained. 9. PEMS should periodically analyze the inspection rates of high-risk and lower-risk lines to ascertain that inspection efforts are being directed appropriately, on average. 10. Before inspection, the exporter may be offered the choice of several inspection instruments, namely (i) complete inspection of nominated lines (item 1 on p. 14); and (ii) before inspection, the exporter can elect to split the consignment (item 2 on p. 14); in addition to the possibility of a complete re-inspection upon replacement of a line after detection of contamination. 11. Compliance-based sampling requires record keeping at the level of biological and operational resolution, that is, to the level at which patterns of compliance can reasonably be expected to persist. In the case of exported plant products, compliance-based sampling would require record keeping for growers, regions, and possibly sub-regions, amounting to a substantial impost upon the regulator. The department should not use compliance-based sampling for exported plant products.
Related Documents	*ISPM 31, Plant Export Operations Manual*
Report Complete	

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	DAWR/MPI Endorsement ( ) Yes ( ) No	Date:
	Report published	Date:

1501E: Compliance and risk-based sampling for horticulture exports

CEBRA Project 1501E Deliverable 7: Final Report

Andrew Robinson, CEBRA, The University of Melbourne

October 26, 2017

Executive Summary

This report focuses on the inspection of export goods for destination countries that do not specify inspection sampling rates for those goods. Two issues are tackled, namely, (i) what is the appropriate level of sampling for consignments that comprise mixes of products, and (ii) whether there is any scope for the use of compliance-based sampling for inspection of plant products that are to be exported.

Part A: Sampling mixed consignments

It is possible that the sampling of mixed consignments can be carried out in a way that satisfies Australia's obligations under the International Standards for Phytosanitary Measures (ISPM) No. 31 (FAO, 2008).

- The current policy of allowing the exporter a choice of 600 units or 2% inspection *does not* satisfy Australia's obligations under ISPM 31.
  - Exporters will most likely choose the least stringent protocol. When 2% of the total unit count is less than 600 units, an inspection of 2% *does not* have a 95% chance of detecting contamination at a rate of 0.5% or higher.
- Inspection of a simple random sample of 600 units from a mixed consignment *does* satisfy Australia's obligations under ISPM 31.
  - The obligations refer to the consignment, not to the lines within the consignment.
  - However, if the 600-unit inspection detects contamination then the entire consignment should be rejected. A practice of dropping or replacing a contaminated line *does not* provide a 95% chance of detecting contamination of 0.5% or higher in the un-sampled units.
  - In order to provide an appropriate level of protection within a system that permits dropping or swapping lines, it would be necessary to (i) verify that cross-contamination cannot have happened, and (ii) inspect 600 different units after dropping / swapping.
- Stratification of a mixed consignment into lines, splitting a 600-unit sample proportionally to line volume between the lines, and inspecting a simple random sample from each line to a total of at least 600 units (rounding fractional units up), is a reasonable device to handle the biosecurity risk of mixed consignments.
  - DAWR should consider using PEMS to monitor the sampling effort devoted to different products, and directing inspection efforts specifically or generally to ensure that reasonably up-to-date information about apparently low-risk products is maintained.
- Most commonly, the samples taken for inspection are clustered by packaging, e.g., selection of a number of crates of fruit. Such a sample design is called *cluster sampling.*
  - A clustered, 600 unit inspection provides a 95% chance of detecting randomly distributed contamination at a rate of 0.5% or higher.
  - A clustered, 600 unit inspection *does not* provide a 95% chance of detecting clustered contamination, e.g., contamination that is transmitted by contact within crates, at a rate of 0.5% or higher.

Part B: Compliance-Based Sampling

It is unlikely that compliance-based sampling, such as the CSP algorithms employed by Imported Plant Products, can be successfully implemented in the export space.

- It would be necessary to collect data at an unprecedented level of detail from each consignment, including, for example, the supplier and geographical region of each line.
- Even then it would be necessary to assume that inspection history was in some way continuous within supplier and region, from consignment to consignment. The biological variability of the underlying system mitigates against this assumption.

List of Recommendations

Acknowledgments

The author is grateful to the following Department of Agriculture and Water Resources personnel for their contribution to this work: Julia Lenton, James Allan, Chandra Balivada, Russell Cant, Adam Dawes, Sricharan Erra, Andrew Loch, Kyra Miles, and Carlos Solorzano. The author also greatly appreciates the contributions of the following Authorised Officers: Mark Avasalu, Shaun Browne, Jesse Hall, Joe Saina, and Greg Sinnott. Rob Cannon and an anonymous reviewer provided very helpful review comments.

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Glossary

AO Authorised Officer — an individual who is authorised to carry out inspections for goods for export on behalf of the department. 9, 15

cluster sampling Selection of units by clusters, and inspection of all the units within the clusters. A common biosecurity example is the selection of fruit by boxes, and the inspection of all units of fruit within the box. i, 6, 10

compliance-based sampling Selection of sample units in a pathway with probability depending in some way upon the expected compliance of the pathway. i–iii, 1, 15

cross-contamination The infestation of compliant lines arising from their proximity to other already infested lines and insufficient biosecurity protection. i, 2, 14

CSP Continuous Sampling Plan, the compliance-based sampling regime that has been used by DAWR in the imported plant product program (see, e.g., Robinson et al., 2012, 2013; Arthur et al., 2013). ii, 15

EXDOC EXDOC is the previous data management system for collection and storage of RFP information. v, 1, 3, 5, 9, 18, 19, 25

IBIS International Biosecurity Intelligence System, the software-based web crawling tool developed by CEBRA to locate and curate early-warning signs of pest activity globally (see Lyon et al., 2013). 9

mixed consignment A consignment that comprises lines from multiple classes of goods — see Appendix B. i, ii, 1, 2, 5, 9, 10, 13

OI Official Inspector — a department inspector. 9

PEMS PEMS is the Plant Export Management System, which is supporting EXDOC. i, ii, v, 1, 3, 5, 9, 13, 18, 19, 25

RFP The Request For Permit indicates the exporters intent to export the prescribed goods. v, 2, 3, 10, 15, 25

sensitivity The sensitivity is the probability that contamination is detected, given that it is present in the consignment at a certain level, which is specified as a percentage of contaminated units. In this report, the desideratum is assumed to be 95% sensitivity at 0.5% contamination, meaning that if 0.5% or more of the units in the consignment are contaminated, then the consignment will be rejected with probability 0.95 (95% of the time). ii, 6–8, 10, 13

simple random sample Also SRS, a sample of fixed size n taken from a population such that all possible combinations of n units are equally likely to be selected. E.g., one could number all the N units in the population, randomly select n integers from $1 \ldots N$ without replacement, and then inspect the units corresponding to the n integers thus selected. N.B., an SRS is a *high bar* to attain and delivers great statistical robustness. i, 6, 10

stratification The division of a population into non-overlapping groups , or strata, in order to improve overall precision or develop estimates for groups within the population. i, 2, 9–11

Chapter 1

Introduction

1.1 Scope

This report focuses on the inspection of export goods for destination countries that do not specify inspection sampling rates.

1.1.1 Part A: Sampling (mixed) consignments

Expected output: Recommendations on sampling methodologies that can be applied to consignments of mixed goods (and small consignments) to issue phytosanitary certification with a 95% level of confidence that there is less than 0.5% level of non-compliance with importing country requirements (potentially using historical compliance data).

This will involve:

- providing recommendations on a sampling rate appropriate to the size or composition of the consignment;
- providing recommendations on how to determine which commodities within a mixed consignment should be inspected and how many of each; and
- advising as to what impact the recommended changes would have on the level of confidence that there is less than 0.5% level of non-compliance.

1.1.2 Part B: Compliance-Based Sampling

Expected output: Recommendations as to the feasibility of using compliance data captured using PEMS to implement compliance-based sampling.

This will involve:

- assessing whether trends can be identified according to factors that may influence compliance; and
- assessing potential for compliance data to be utilised to vary the sampling rate required to issue phytosanitary certification with a 95% level of confidence that there is less than 0.5% level of non-compliance with importing country requirements.

1.2 This Report

The balance of this report is structured as follows. In the next section I summarize the key elements of the export inspection process. Then I analyze EXDOC and PEMS data sources to report the characteristics of the plant export pathways. Finally I discuss the issues of sampling mixed consignments, and whether or not compliance-based sampling might be useful in this context.

Chapter 2

Summary of Inspection Process

A brief summary of the current practice for the inspection process follows.

- Exporter submits a NOI (Notice of Intention to Export Prescribed goods) or its electronic equivalent RFP (Request for Permit), which indicates the exporters intent to export the prescribed goods.
- The Phytosanitary Certificate is issued by the department upon successful completion of requirements[1]
  - The requirements may comprise the sighting of appropriate documentation and/or physical inspection of a sample of the goods.
  - The nature of the requirements depends on importing country requirements. For example, United Arab Emirates requires that inspected mangoes be split to ensure that the seed does not carry any mango seed weevil.
  - Some destination countries specify exactly what kinds of inspections are required, for example, visual inspection of a 600-unit random sample for citrus to China.
  - Other countries allow the department to set an appropriate inspection regime. For such destinations, the department applies ISPM No. 31 and allows the exporter to choose between a 600-unit inspection or a 2% inspection.[2]
  - The unit of inspection depends on the commodity. For example, in mangoes the unit of inspection is the fruit item, whereas in blackberries, the unit of inspection is the punnet, regardless of the size of the punnet.
- If contamination is detected by inspection then the RFP is not authorized.
- Exporters are consolidators of export consignments, which can comprise a wide range of products.
  - For inspection, mixed consignments are informally stratified into risk classes (e.g., fruit fly hosts, root products, leafy greens), and the 600-unit / 2% sample is split between the lines that comprise each stratum. This stratification is possibly inconsistently applied by Authorised Officers.
- Products are commonly sourced from growers at local markets in an ad-hoc way.
  - Growers often produce fruit and vegetables for targeted markets and exporters may preferentially source commodities from such growers.
- If the consignment comprises multiple lines, and contamination is detected in one line, then the line may sometimes be replaced or dropped altogether, and the consignment presented again. A consignment that is re-presented following this line-replacement practice requires a completely new 600-unit sample *and* assessment against the possibility of cross-contamination.
- In order to save time, the exporter may request that the sampling and inspection be performed by an Authorised Officer approved by the department.
- There is considerable variation in the goods presented for inspection at the different regions. For example, Brisbane is a Pacific Island serving port, with some products sent to the Middle East.
- Commonly, exported goods are inspected upon arrival at the importing country.

[1] See `http://www.agriculture.gov.au/export/controlled-goods/plants-plant-products/exportersguide`

[2] A departmental reviewer noted: "2% sampling rate applies only at package level, i.e. 2% (minimum 3 packages) of the number of packages in each consignment as per Plant Export WI 'Sampling and inspection for export certification of completed consignments and lots (fresh fruit and vegetables)." However, based on my interviews of department staff, the 2% sample is being applied at the unit level, not at the package level.

Chapter 3

Data Analysis

This section provides statistical summaries of the two databases that house data relevant to the management of biosecurity risk for exported plant products, namely EXDOC and PEMS (Plant Export Management System).

I received a data dump from EXDOC that comprised 378,000 RFPs and information concerning 1.26 million lines. I used only two financial years of these data (2013–14 and 2014–15), to keep the results timely. The analysis excluded all products classed as foliage, flowers, meal, oil, and nursery stock, as these products are not in the scope of the project. The data from PEMS comprised about 16500 lines and information for 4600 RFPs.

The total analysed data comprised about 77,000 RFPs, 280,000 lines, and 233 products, which were classified into 118 product classes. These product classes form the basis of the product combinations (see Appendix B).

3.1 Product Combinations

The goal of this section is to determine the variety of combinations of products within consignments, and whether these vary systematically by state or destination country. Table 3.1 shows the count of consignments by pathway and state. The balance between air and sea differs markedly from state to state, and more than half of the consignments in this dataset departed from Victoria.

Table 3.1: Count of plant export consignments by pathway (AIR/SEA) and state.

Pathway	ACT	FNQ	NSW	NT	QLD	SA	TAS	VIC	WA
Air	0	455	11777	0	9346	963	1550	21976	2959
Sea	1	107	1915	6	2689	3572	869	13315	5691
Total	1	562	13692	6	12035	4535	2419	35291	8650

There were about 9,800 different combinations of products in the 77,000 RFPs. Table 3.2 shows the complexity of the pathways by reporting the consignment size, measured as number of lines, by departure state. The distribution of consignment sizes varies from state to state; each is dominated by single-class consignments. Table 3.3 shows the complexity of the pathways by reporting the number of unique combinations of product classes from each region and in each product count range. The pathway for each region is highly variable in its combinations of classes.

Graphical summaries of the distribution of the data, reproduced in the Appendix, provide the following points.

1. In general, product classes appear in a wide array of different product combinations.
2. Each state shows considerable variability in terms of the number of lines per consignment.
3. Consignment sizes by destination country show considerable variability in terms of the number of classes per consignment.

Table 3.2: Consignment complexity, measured as number of classes per consignment, by departure state.

Region	1	2	3–5	6–10	11–20	20–39	40–59	60+
ACT	1	0	0	0	0	0	0	0
FNQ	180	18	75	76	69	143	1	0
NSW	6005	2563	1591	1723	1507	153	7	0
NT	1	3	2	0	0	0	0	0
PEMS	1664	112	104	117	114	83	0	0
QLD	7789	982	957	638	993	656	16	0
SA	4023	35	1	0	0	0	0	0
TAS	2298	10	28	21	49	2	0	0
VIC	25289	1795	1835	1141	1195	274	0	0
WA	6997	680	738	120	115	0	0	0
Total	54247	6198	5331	3836	4042	1311	24	0

Table 3.3: Pathway complexity, measured as number of combinations of classes, by departure state.

Region	1	2	3-5	6-10	11-20	20-39	40-59	60+
ACT	1	0	0	0	0	0	0	0
FNQ	8	10	20	24	25	108	1	0
NSW	43	203	896	1258	1343	148	6	0
NT	1	2	2	0	0	0	0	0
PEMS	25	32	54	70	90	74	0	0
QLD	37	124	484	548	806	580	16	0
SA	17	8	1	0	0	0	0	0
TAS	10	6	21	19	40	2	0	0
VIC	49	161	640	826	1078	257	0	0
WA	23	24	58	101	96	0	0	0
Total	214	570	2176	2846	3478	1169	23	0

4. Victoria dominates the other states in terms of consignment count, and its most significant markets are Hong Kong and Singapore, followed by Japan and the UAE.

5. New South Wales is the second highest, and its most significant markets are Hong Kong and Singapore, followed by the UAE.

6. Queensland is third, with Singapore, New Zealand, Hong Kong, Papua New Guinea, and UAE.

7. Most destination countries receive consignments from most of the states, with most of their consignments coming from Victoria; Papua New Guinea and New Zealand (both dominated by consignments from Queensland) are the notable exceptions.

8. The consignments that are combinations of six or more classes are dominated by traffic from Queensland to Papua New Guinea, New South Wales to Singapore (and some to Hong Kong), and Victoria to Singapore and Thailand.

9. Analysis of the patterns of co-occurrence of product classes within consignments suggested the following combinations are common (Figure A.5):

    - Prunes, walnuts and hazelnuts;
    - Mixed fruit and mixed vegetables;
    - Bananas and bitter lemons;
    - Dates and pistachios;

- Chokos and passionfruits;
- Basil, mint, oregano, thyme;
- Thyme with rosemary or sage;
- Spinach and rocket, often also with lettuces and/or salad mix;
- Capsicum & chilies with cauliflowers or tomatoes; and
- Lettuces with mushrooms.

3.1.1 Caveats

The EXDOC data set is likely to be unbalanced relative to the total consignments presented for inspection, because consignments that failed inspection were not recorded in the database. Therefore it is impossible to know the true rate at which different classes or combinations of classes of consignments have been presented.

3.2 Inspection Outcome

PEMS includes more information on the consignments than does EXDOC, and of greatest interest was whether or not an inspection was carried out, and what was the outcome of the inspection. A total of 278 lines reported failed inspections.

I intended to pursue a formal analysis of the inspection decision, but the following realisation, determined during visits to the regional offices, dissuaded me. Whether or not a line is inspected in the first instance depends on the combination of product and destination country, because of specified protocols. If no protocol is in place then whether or not a line is inspected depends on that nature of the other lines within the consignment, as documented in this report - for example whether or not there are fruit fly hosts. Mixed consignments are generally not protocol so this would be the status quo. Hence any analysis of the inspection decision process will be muddied by these factors.

Second, the inspection outcome depends on the amount of effort dedicated to the inspection, here meaning the number of items inspected. PEMS records the quantity sampled but inspection of the sample sizes for the 111 lines that failed suggests that sometimes the entire sample number has been recorded and sometimes the number actually examined has been recorded. Formal analysis of the inspection outcomes will be muddied by these elements.

Hence I do not undertake further analysis of the inspection outcome data at this point in time.

Chapter 4

Sampling Considerations

4.1 Background

The purpose behind the imposition of a sample-based inspection regime is not to find all contamination, rather, the purpose is to deliver statistical confidence that the pathway-level contamination rate is below a nominated level. The level is that which arises from the inspection of every consignment with probability of detecting contamination at 0.5% or above being 95%. The inspection is performed on the consignments but the controls are applied to the pathway.

In this chapter, I assume that all inspections are carried out without error, and that if contamination is present on an inspected item then it is detected with 100% surety. This strong assumption can be weakened with some relatively straightforward adjustments to the report, but it is beyond the scope of the present work to do so.

4.2 On Random Sampling and Cluster Sampling

The ISPM 31 standard assumes that the selection of the sample of 600 units is a simple random sample, meaning that all possible combinations of size 600 of the units are equally likely (FAO, 2008). In practice this process is never achieved; commonly units are packed in boxes, and samples are taken for inspection by selecting the needed number of boxes to make up the unit count, and inspection is performed on all the units in the sampled boxes. Formally, this sampling technique is called *cluster sampling* (Cochran, 1977).

If the contamination is randomly spread among the units in the consignment, then cluster sampling will achieve the nominal sensitivity, that is, the fact that the units are selected in clusters will not impact upon the inspection regime. However, if the contamination is clustered, then the sensitivity of the 600-unit sample will be reduced, and the degree of reduction depends on the degree of clustering.

Specifically, cluster sampling is *less sensitive* than simple random sampling when the contamination within a consignment itself is clustered; for example, the contamination could be concentrated in one or a few boxes. However, cluster sampling is as sensitive as simple random sampling when the contamination within a consignment is either homogeneous or random. This is because the units in the cluster are not more likely to be similar to one another.

It is clear that the degree of clustering of contamination will likely depend on the supply-chain logistics. Mobile pests are more likely to be detected during pre-export processing, and the degree of mixing that most products undergo also may support an assumption of random contamination within lines.

Recommendation 1. Sampling by clusters of units will not achieve nominal sensitivity when contamination is clustered. If it is possible that the regulated pests of concern occur in a clustered pattern within the consignment then the inspectors should take every reasonable pain to ensure that the sampling is not clustered. This prescription may be more important for some commodities than others.

4.3 600 units or a 2% sample?

As noted above, exporters can select between a 600-unit or 2% sample for the inspection of consignments for export of products to countries that do not specify a sampling rate[1]. Exporters will generally select the 2% rate if that results in fewer than 600 units being inspected, which will be true for any consignment that comprises less than 30,000 inspection units.

Figure 4.1 shows the effect of taking a 2% simple random sample instead of a 600-unit sample based on the size of the consignment. It is computed directly from the Binomial distribution. The Figure shows that a 2% simple random sample *reduces* the probability that a contamination rate of at least 0.5% will be detected. The nominal probability of detection, 95%, which reflects Australia's obligations under ISPM 31, is indicated by the horizontal grey line. The actual probability of detection changes with the consignment size, as shown by the curve. The curve shows that selection of a 2% sample will not provide 95% probability of detecting a contamination rate 0.5% or lower unless the consignment size is 30,000 or more. For example, if the consignment size is 10,000 units, then inspection of a 2% sample corresponds to inspection of 200 units, which has only a 62.5% chance of detecting contamination that is 0.5%.[2]

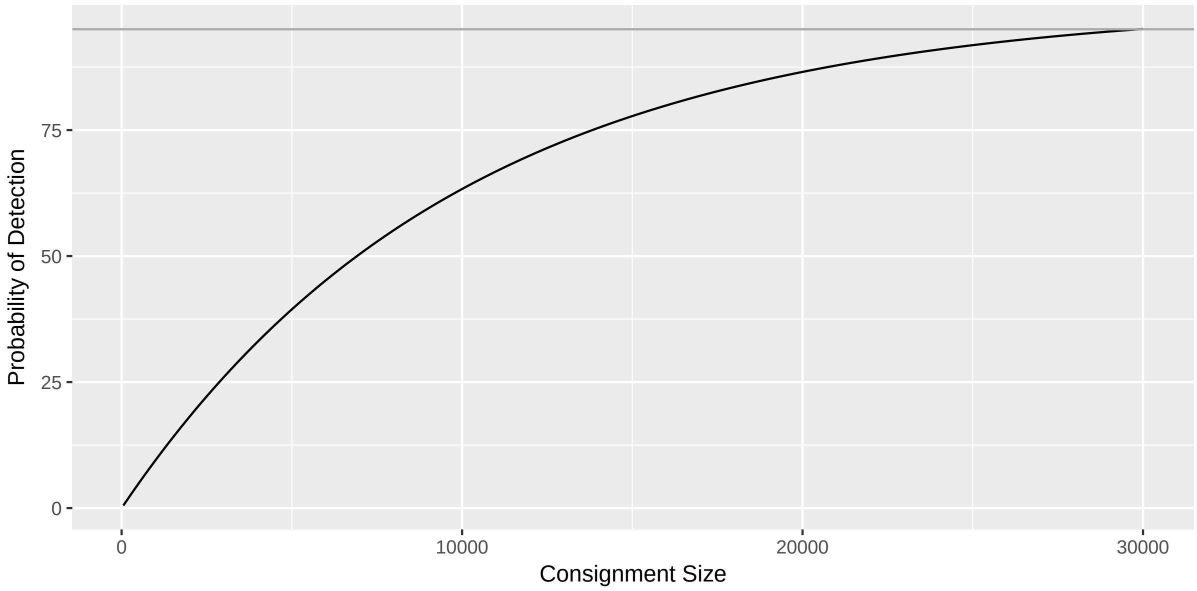

Figure 4.1: The probability of detecting contamination of 0.5% from a 2% simple random sample against population size is presented by the curve. The grey horizontal line shows the nominal probability, which is 95%

Recommendation 2. Where previously a choice between inspection of a 600-unit or a 2% sample had been offered to the exporter for exported plant products, the department now should require a 600-unit random sample. If the consignment size is known then a smaller sample size may be possible, see Figure 4.2. Furthermore, the sample should be taken as a simple random sample to the best of the inspector's ability.

If the consignment size is less than 2000 units, then the nominal sensitivity can be achieved with fewer inspected units (see ISPM 31 FAO, 2008). Figure 4.2 shows the required sample size as a function of the size of the consignment. The jagged line is created by the conversion of the limiting defective rate (0.5%) to a whole number of defective units — for example, when N is 1000, the number of defectives is at the cutoff 5, but when N is 999, it is rounded down to 4.

Table 4.1 shows the required sample sizes for the upper limit of the curve in Figure 4.2, to simplify access. Values between the dots are well approximated by the following relationship:

[1] Please note the caveat on p. 2 about possible variation between work instructions and practices.

[2] A departmental reviewer pointed out that it may be helpful to look into how to define the scope of products, distribution of biosecurity risks involved, and package sizes (e.g., the number of units per box) for 2% samples, and to consider theoretical work to develop some risk-based cluster sampling strategies in an extension project.

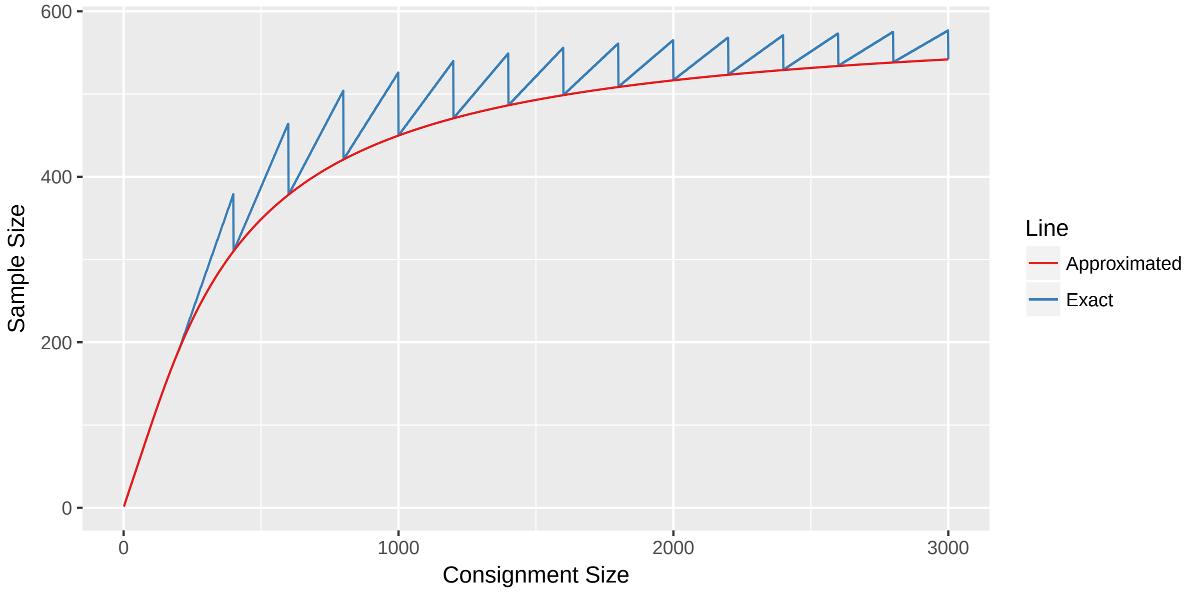

Figure 4.2: The necessary sample size (y-axis) to achieve nominal probability (95%) of detecting contamination at 0.5% against the consignment size (x-axis).

$$n = \left(1 - (1-\beta)^{1/d}\right) \times \left(N - \frac{d-1}{2}\right) \tag{4.1}$$

where the goal is to detect d contaminated items from N with probability β[3]. For example, If N is 750, β is 0.95, and d is $750 \times 0.005 = 3.75$ then $n = 411.9$.

Both Table 4.1 and Figure 4.2 show the use of the Hypergeometric distribution as documented in ISPM 31.

Table 4.1: The sample size (n) required to detect 0.5% contamination with at least 95% probability based on the number of units in the consignment (N). The approximation is based on Equation 4.1.

N	n	Approximation
200	191	190.000
400	311	310.169
600	379	378.327
800	421	420.913
1000	450	449.818
1200	471	470.663
1400	487	486.385
1600	499	498.657
1800	509	508.499
2000	517	516.566
2200	524	523.297
2400	529	528.998
2600	534	533.888
2800	539	538.129
3000	542	541.842

Recommendation 3. For smaller consignment sizes, say 2000 or fewer units, the nominal sensitivity can be achieved with fewer than 600 units of inspection as long as the number of inspection units in the

[3]The author is grateful to Rob Cannon for pointing out this useful approximation.

consignment is known. PEMS should compute and report the needed sample size to the inspector, with a simple rule of thumb applied as a backup, such as sample all units if the total number of units $N \leq 450$; 450 if $450 < N < 1000$; and 600 if $N > 1000$.

Hereafter in this report, wherever reference is made to a 600-unit sample, it should be understood that the reference is short-hand for "600 unit sample or less, depending on the size of the consignment, as per Table 4.1."

4.4 Information Sharing Network

As noted above, when a mixed consignment is presented, the inspector commonly stratifies it according to the perceived risk in terms of both contamination rate and consequences. This stratification is performed subjectively and is based on the inspector's professional experience and knowledge.

Implicit in this subjective stratification is that the inspector will have sufficient knowledge about the contamination rates and consequences of all the goods in the consignment. However, these rates and consequences are numerous: there are about 675 products appearing in EXDOC, and the risk and consequences can vary between and within regions, and between seasons.

It is reasonable to expect that the development of a professional network would assist both official and authorized inspectors in forming an opinion about the relative risk of the lines presented in a consignment. Such a network would permit the rapid sharing and assessment of information that might lead to a recognition of changing risks, or a speedy debunking of unverified but alarming rumours.

Recommendation 4. Communication between inspectors is paramount for ongoing training, developing culture, and sharing information about risky pathways. The department should facilitate communication between inspectors by some means, including but not limited to an official network along the lines of IBIS.

Presently, the only means of communication between AOs and OIs is word of mouth. Relying on informal communication networks runs the risk of creating and perpetuating hierarchies and rumour mills within the system, both of which are deleterious to the satisfactory maintenance of Australia's regulatory responsibilities. Creation by the department of some kind of opt-in communication network, along the lines of the International Biosecurity Intelligence System (IBIS Lyon et al., 2013), would mitigate against these effects.

Recommendation 5. Use PEMS to provide automated feedback to pathway managers and inspectors about interception records and inspection patterns. This feedback could be graphical on a home-page, with click-through links to inspection and interception counts by region, supplier, or product, and hyperlinks to local issues of note.

4.5 On-arrival inspections

The department has recognised the general value of audit or follow-up inspections in order to measure operational and regulatory performance. For example, endpoint surveys are carried out in the international passengers and mail pathways, and cargo compliance verification is carried out in sea cargo. No such inspections are undertaken for exported goods. However, exported consignments are sometimes inspected upon arrival at the importing country. In some senses, the on-arrival acceptance of exported goods could be considered a gold standard for export operations. If the department were able to reliably obtain inspection outcome results that could be traced back to the exported consignment information, then the on-arrival inspection could be used as an endpoint or leakage style survey, and provide essential information about the quality of export intervention. However, operationalisation of this initiative will be difficult owing to its need for multilateral data sharing arrangements.

Recommendation 6. Inspection data are vital for risk-based management of biosecurity pathways. The department should try to develop multilateral arrangements for sharing appropriate inspection data with trusted trading partners, or develop simple approximations using reported inspection results and information about the import inspection frequency of the importer. Knowing what shipments failed or required treatment would also provide useful feedback to producers and others associated with the pathway.

Chapter 5

Sampling Mixed Consignments

5.1 Background

The challenge of sampling inspection is greatly complicated by the presentation of multiple products in single consignments. Up to 90 products have appeared in single RFPs. The analysis summarised in this report shows that a substantial range of combinations of products are aggregated and exported as single consignments.

The inspection regime, briefly, is as follows. The exporter is permitted to choose the sampling rate (namely, 600 units or 2%). The inspector then chooses which lines to inspect and in what quantities. The approach taken by the department's inspectors is, overall, to stratify the goods into two to four classes, for example in Qld: fruit-fly hosts, roots, leafy vegetables, and onions/garlic. Sample counts are then usually taken as proportional to the relative volume of the lines in the stratum. Inspection is visual and inspectors are encouraged to investigate further if they suspect infestation.

5.2 Principles

Although it may seem counter-intuitive, the selection and inspection of a simple random sample of 600 units from a mixed consignment *does* satisfy Australia's obligations under ISPM 31. This is because the consignment is considered to be a population from which the sample is taken, and so far as the statistical theory is concerned, the make-up of the population is irrelevant. This point bears emphasis: sampling theory applies to *any* correctly obtained sample of *any* population.

However, as noted above, if the sample is not a simple random sample then it is likely that the sampling and inspection will fall short of regulated sensitivity. It is common, for example, for inspections to be carried out on collections of items such as boxes of fruit. The inspection of a box of items is called *cluster* sampling (Cochran, 1977), and although cluster sampling is a valid sampling technique, if the design sensitivity against all regulated pests is to be retained then the sample size must be increased.[1]

5.3 Operational Considerations

When presented with a mixed consignment, the inspector will informally stratify the lines into risk classes (for example, fruit fly hosts, root products, leafy greens), and then split the 600-unit / 2% sample between the lines that comprise each stratum.

This practice presents a risk to Australia's compliance under ISPM 31 because it is possible that some strata contain lines for which the contamination rate is high but the invasive consequences are low. For example, anecdotal evidence suggests that the failure rate of leafy green vegetables is higher than fruit-fly hosts, however, if a fruit fly host is contaminated then the impact is far greater. Therefore, inspectors tend to focus their efforts where the consequences are high rather than where the contamination rate is high.

Overall, stratification seems like a reasonable compromise to make. It will impact upon Australia's regulatory compliance in ways that are difficult to assess succinctly but are nonetheless likely to be

[1] A departmental reviewer recommends further work to determine how much the cluster sampling rate would increase with homogeneity of biosecurity risks as the consignment changes from random to moderately clustered so that the 95% confidence is maintained.

negligible. It seems reasonable to direct inspectors to focus their sampling efforts upon random samples of lines that their professional experience suggest are more likely to have contamination of importance to Australia's national interests.

Finally, it is important to note that on average, if appropriately applied, stratification does result in appropriate consignment-level protection (see following section) but it does not achieve nominal stratum-level protection, because the sample sizes within the strata are naturally smaller than the nominal 600 units.

5.4 Sampling Multiple Lines

I now discuss the conditions under which it is reasonable to sample across multiple lines as though they were a single mixed line.[2] On the topic of mixed heterogeneous lines, ISPM 31 says

> "A lot to be sampled should be a number of units of a single commodity identifiable by its homogeneity in factors such as:
>
> - origin
> - grower
> - packing facility
> - species, variety, or degree of maturity
> - exporter
> - area of production
> - regulated pests and their characteristics
> - treatment at origin
> - type of processing.
>
> The criteria used by the NPPO to distinguish lots should be consistently applied for similar consignments.
>
> Treating multiple commodities as a single lot for convenience may mean that statistical inferences can not be drawn from the results of the sampling." (FAO, 2008, p. 7)

The goal of this section is to demonstrate that ISPM 31's restriction on mixing heterogeneous lines (lots) is too restrictive, and that there are ways of sampling mixed heterogeneous lines that do achieve the required sensitivity against contamination.

The ISPM 31 sample size calculations are derived from a body of work called "design-based sampling theory". However, there is no statistical constraint or requirement for homogeneity of a sampled population within design-based sampling theory (Cochran, 1977). Indeed, samples are commonly collected and analyzed across substantially heterogeneous populations, such as human and economic populations in official statistics, and forest communities in natural resource management. The only constraints that are imposed by statistical theory are (i) that the sample be taken according to one of a number of different kinds of random sample designs, for example as detailed in ISPM 31, and (ii) if contamination is detected in any of the units sampled, then *all* of the lines from which the sample was taken must be rejected.

(NB: There are non-statistical circumstances in which treating lines separately makes operational sense. One is that the products may carry different kinds of pests that themselves present different risks. Another is that the exporter may not wish to take the chance that contamination in one line will affect the treatment of all of the lines. However, if the lines are sufficiently similar that they are likely to be vectors for the same kinds of pests, then there is no statistical or operational reason to treat them as separate lines.)

Next I develop a case study to show a situation for which *if* the sampling is done appropriately, then treating multiple lines as a single line for the purposes of sampling does not carry statistical risks, so long as if contamination is detected in *any* of the units sampled, then *all* of the lines from which the sample was taken are rejected. A proof of the generality of the case study can be found in Appendix C.

[2] I'm grateful to Rob Cannon for very useful discussions that led to the development of the following material.

5.4.1 A Worked Example

We want to ensure that the sensitivity is not less than 95% if we are sampling correctly from heterogeneous product lines. Consider the situation of two product lines, labelled 1 and 2, with 10000 units and 20000 units respectively. Set the joint contamination to be 0.5%, which is the amount that the usual random sample of 600 units will detect 95% of the time. [3] This means that between the two lines, there are 150 contaminated items.

Now we ask: what effect does changing the relative contamination of lines 1 and 2 have upon the sensitivity of the test, given that the overall contamination is fixed at the nominal 0.5%? And, if the relative contamination affects the sensitivity, then under what circumstances, and in what ways?

What we want to see is a situation in which the sensitivity of the test is 95% or higher, regardless of the relative contamination rates of product lines 1 and 2. If this is true then we can allocate 600 units to the mixed lines with confidence, knowing that the sensitivity is 95% or above.

Figure 5.1 provides insight to the results for this situation. It shows two different allocations of sampling units to the product lines (the two different coloured lines on the graph) and for each, the effect upon the sensitivity (y-axis) of the contamination of line 1 (x-axis). The blue scenario shows the effect of proportional allocation (200 units to line 1, 400 to line 2), and the red scenario shows the effect of equal allocation to each line (300 units each).

Recall that we want the sensitivity (y-axis) to be greater than 95% in order for there to be at least 95% probability of detecting the contamination. The x-axis shows the contamination of product line 1. Recall that the total contamination is fixed at 0.5% (the vertical dotted line). If the contamination of line 1 is 0.5% then the contamination of line 2 must be 0.5%, and the lines are homogeneous. If the contamination of line 1 is below 0.5% then the contamination of line 2 must be above 0.5%, because the overall contamination is fixed. So, the lines are homogeneous if $p_1 = 0.5\%$ and heterogeneous otherwise.

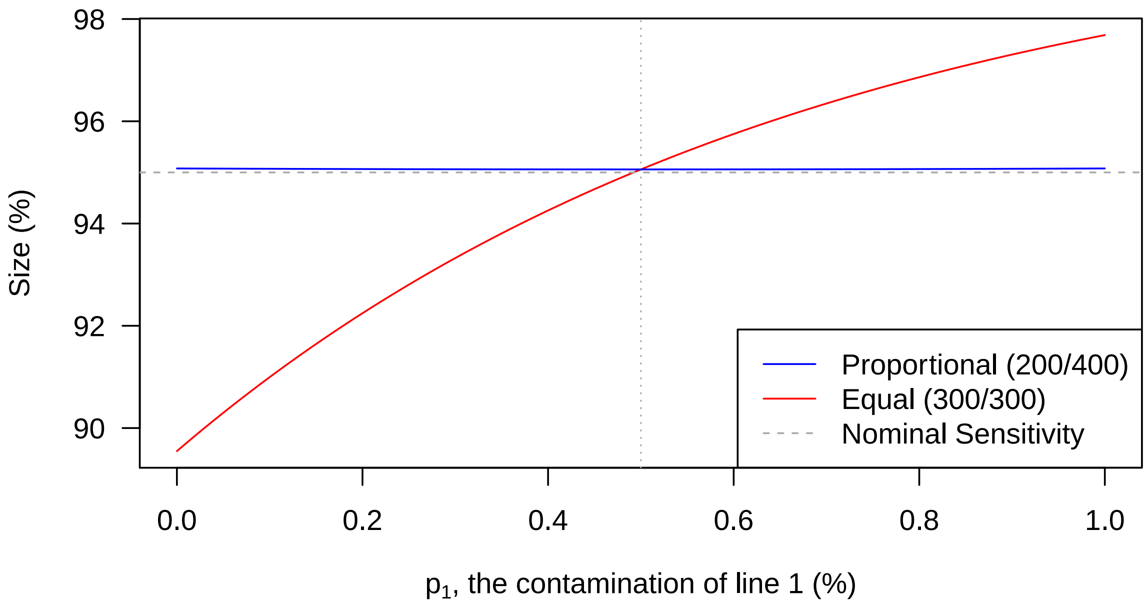

Figure 5.1: The effect upon the sensitivity (y-axis) of the contamination of line 1 (x-axis) for two different allocation rates of 600 sampling units to the product lines. Note, the nominal sensitivity is 95% (dashed horizontal grey line) and the overall contamination p is set at 0.5% (dotted vertical grey line).

Briefly, the results are as follows. When the sample units are allocated proportionally to the product lines (blue scenario), the test achieves nominal sensitivity or better, regardless of the value of p_1, because the blue line on the plot is always above 95%. That is, sampling mixed heterogeneous lines as though they were a single line is safe so long as sampling is proportional to the volume of the lines.

When the sample sizes are weighted in any other way, the relative contamination has a strong effect. As more units are allocated towards the more highly contaminated line, the size of the test decreases

[3] 600 units is actually conservative — we can achieve nominal 95% sensitivity against 0.5% contamination with 598 units. But 600 units provides a more familiar narrative.

and it becomes more sensitive. So, if the relative contamination of the lines is known, then allocation of relatively more effort towards the more contaminated line produces a test that performs as well as or better than nominal.

To sum up, in this example, if nothing is known about the relative contamination rates of the product lines in a mixed consignment, then proportional allocation is best and provides the expected performance in this situation. Appendix C provides mathematical proof of the generality of this result.

Recommendation 7. That mixed consignments have the 600-unit random sample be split proportionately between the lines, rounding fractional samples up, and a simple random sample be taken within each line to the best of the inspector's ability.

However if products are rarely sampled then it will be difficult to develop institutional knowledge or experience about them. Therefore it may be worth considering using PEMS to keep track of the amount of sampling that has been performed on individual product types and to direct their occasional sampling in order to keep track of their biosecurity status.

Recommendation 8. Use PEMS to monitor the sampling effort devoted to different products, and directing inspection efforts specifically or generally to ensure that reasonably up-to-date information on apparently low-risk products is maintained.

One aspect of asking the inspectors to stratify and choose lines for inspection is the subjective nature of the choice. Humans find it very difficult to choose anything purely at random. There is a chance that apparent patterns of inspection choices, for example away from risky lines, may reflect bias on the part of the inspector.

Recommendation 9. PEMS should periodically analyze the inspection rates of lines to ascertain that inspection efforts are being directed appropriately, on average.

5.5 Alternative Sampling Strategies to Mediate Risk

It is useful to consider the risk problem from the point of view of the consumer and the producer. Here, the producer is the exporter and the consumer is the trading partner, represented by the department. The consumer's risk is the probability that a non-compliant consignment is not detected by the intervention, which depends on the contamination in the consignment and is set at 5% for 0.5% contamination (i.e., 95% probability of detecting 0.5% contamination).

The producer's risk is the probability that a compliant consignment is rejected by the system. Here, no non-zero amount of contamination is accepted, so at the consignment level, the producer's risk is zero. However, in mixed consignments some lines may be compliant and others non-compliant, and the underlying risk of non-compliance may vary from line to line. In this case, the producer's risk is not zero because a line in a consignment may be rejected because it is part of the whole that has been sampled, but the non-compliance was found in a different line.

It seems counter-intuitive to reject an entire consignment on the basis of the failure of a single item in a specific line, but this is the action required to ensure that the pathway receives the necessary regulatory intervention. The operational practice of just rejecting the line is intuitively appealing, but unfortunately *does not* provide pathway-level protection against biosecurity contamination that Australia's trading partners require.

So it would be useful to consider some sampling strategies that retain their sensitivity against biosecurity risk whilst going some way towards reducing the risk faced by the exporter, namely the rejection of a complete consignment based on a single item's failure. That is, to determine whether it is possible to reduce the probability of rejecting compliant lines whilst protecting the consumer's risk.

Two alternative options are possible which would deliver the same level of protection to Australia's trading partners whilst reducing the risk of heterogeneous consignments to the inspection process.

1. Before inspection begins, the exporter can nominate any number of lines for *complete inspection*. All items in these lines are inspected, *in addition to* the 600-unit inspection that is allocated among the rest of the consignment. If contamination is detected in any of the completely inspected items, then the contaminated items must be discarded, and may be replaced by other inspected units, and the line can be exported. If contamination is detected in any of the 600-unit sample, then the lines that were not 100% inspected within the consignment must be rejected. The count of units in

completely inspected lines should not be included for the purposes of computing the consignment size.

- Example: the exporter brings 50 head of celery, 400 apples, and 400 pears. They elect for full inspection of the celery, so all 50 celery are inspected. The 800 fruit are the balance of the consignment, and according to Figure 4.2 the needed sample size is 421.
- One celery fails and is replaced by a new, inspected, head of celery. All the celery have now been inspected. No contamination is detected in the 421 unit sample of apples and pears, and the whole consignment can be exported.

2. Before inspection begins, the exporter can elect to split the consignment into multiple sets of lines, each of which undergoes a 600-unit sample, so long as cross-contamination is not possible.

   - Example: the exporter brings 500 apples and 500 pears. They elect to split the consignment into two for the purposes of inspection. The necessary sample size for a 95% probability to detect contamination at 0.5% is about 354 for each of the two splits (total 708).
   - One of the apples is contaminated, so the apples line must be discarded. The sample of pears is clean and the pears may be exported.
   - Had any number of apples been contaminated, but no pears, then the result would be the same.

Recommendation 10. Before inspection, the exporter may be offered the choice of several inspection instruments, namely (i) complete inspection of nominated lines (item 1 on p. 14); and (ii) before inspection, the exporter can elect to split the consignment (item 2 on p. 14); *in addition to* the possibility of a complete re-inspection upon replacement of a line after detection of contamination.

In any case, the exporter may request inspection of a new 600-unit sample upon dropping or replacing a line, so long as cross-contamination is ruled out.

Chapter 6

Compliance-Based Sampling

6.1 Background

The benefits of compliance-based sampling rely upon the classification of consignments into groups within which there is a priori reason to believe that the patterns of non-compliance are likely to be similar. For example, in the plant import pathways within which the continuous sampling plans (CSP) have been implemented, the imported products are grouped by tariff code, importer, and exporter.

6.2 Recommendation

In order to apply this principle in plant exports, inspection records would need to be kept by state, region, and grower for each line on every RFP. This represents a substantial potential and probably intolerable impost on data capture. Furthermore, contamination patterns are highly volatile across seasons.

There are further operational considerations that mitigate against the deployment of compliance-based sampling in plant exports. For example, should external AO inspections be given equal weight in determining compliance in a risk-based setting? If not, then in what principled way could they be treated differently? For example, AO interception rates may be deflated by early screening, although this might also be true of departmental inspectors.

Recommendation 11. Compliance-based sampling requires record keeping at the level of biological and operational resolution, that is, to the level at which patterns of compliance can reasonably be expected to persist. In the case of exported plant products, compliance-based sampling would require record keeping for growers, regions, and possibly sub-regions, amounting to a substantial impost upon the regulator. The department should not use compliance-based sampling for exported plant products.

Chapter 7

Conclusions

This report focuses on the inspection of export goods for destination countries that do not specify inspection sampling rates.

7.1 Part A: Sampling mixed consignments

The current policy of allowing the exporter a choice of 600 units or 2% inspection does not satisfy Australia's obligations under ISPM 31.

Inspection of a simple random sample of 600 units from a mixed consignment does satisfy Australia's obligations under ISPM 31, provided that the consignment is inspected randomly across the consignment and if contamination is detected the whole consignment is rejected.

Stratification of a mixed consignment into risk classes (e.g., fruit fly hosts, root products, leafy greens), splitting a 600-unit sample proportionally between the strata, and inspecting a simple random sample from each stratum to a total of 600 units, is a reasonable device to focus attention on the pathways that represent a higher risk to Australia's trading partners.

Operational recommendations regarding the implementation strategy and impacts of th e recommendations are presented, including the role of PEMS.

7.2 Part B: Compliance-Based Sampling

Compliance-based sampling is not possible with the current systems, as it would require the collection of an unprecedented level of detail from each consignment. In addition it would be necessary to assume inspection history was continuous within supplier and region, from consignment to consignment when in practice this varies greatly.

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Appendix A

Data Summaries

Figure A.1 shows the frequency distribution, on a logarithm scale, of the consignment sizes by state.

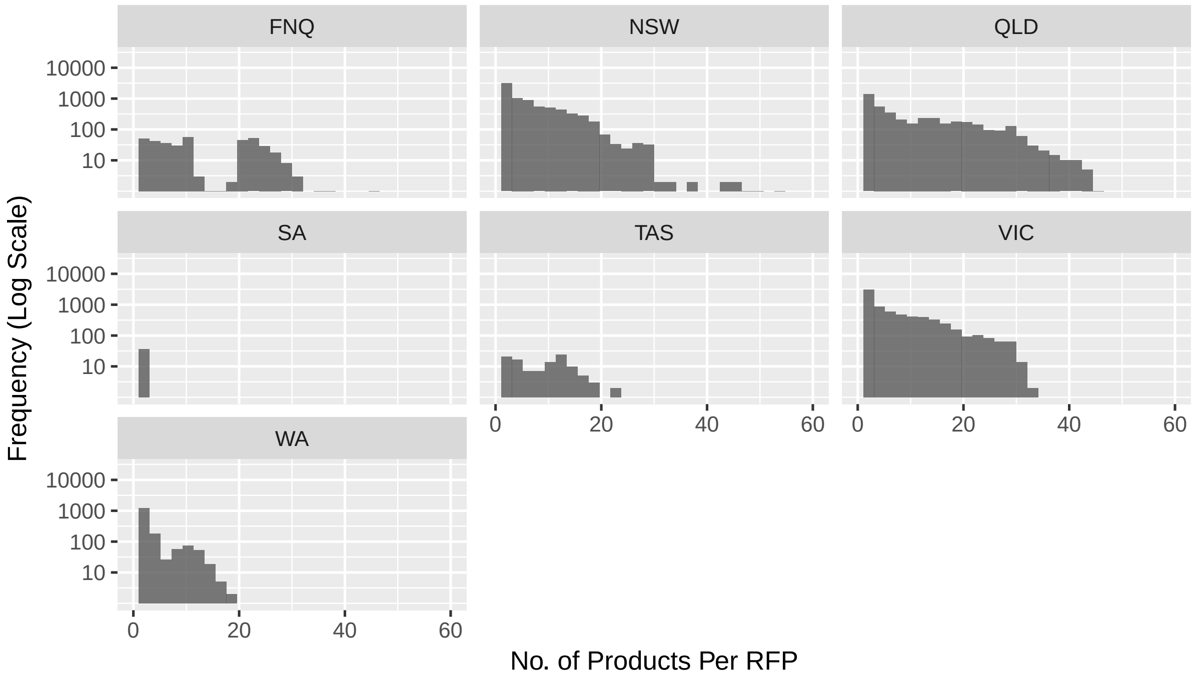

Figure A.1: Product class count per consignment from PEMS and EXDOC, by region, in histograms.

Figure A.2 shows the frequency distribution, on a logarithm scale, of the consignment sizes by destination country, for all countries with more than 120 consignments. Again, each country shows considerable variability in terms of the number of lines per consignment. The total number of consignments for the two years is added to the country label.

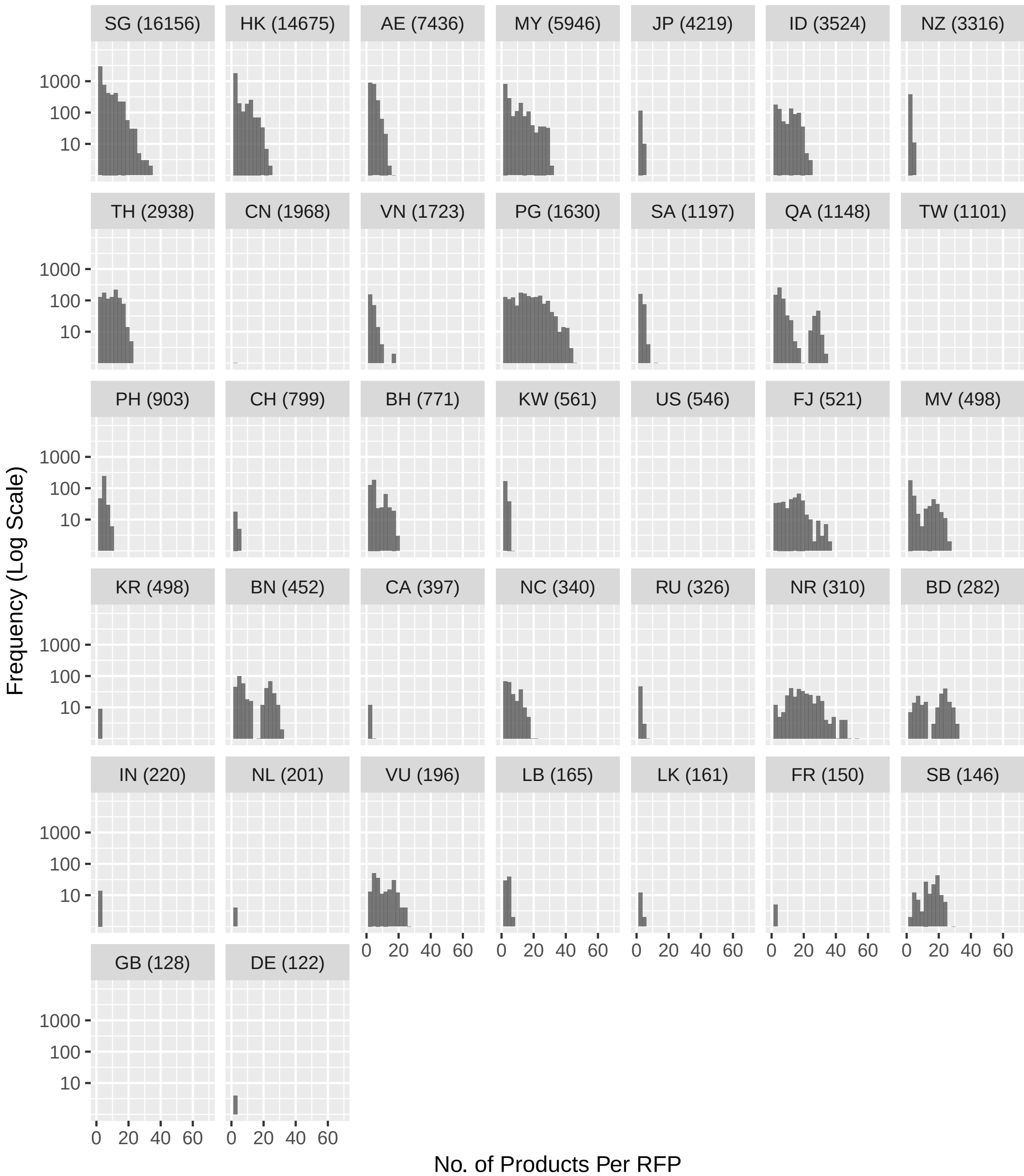

Figure A.2: Product class count per consignment from PEMS and EXDOC, by receiving country, in histograms.

Figure A.3 shows the distribution of consignment counts by region and destination country for all countries with 100 or more consignments and the largest five states by consignment count. Hong Kong, Singapore, and Victoria dominate the patterns, but most countries receive consignments from most states.

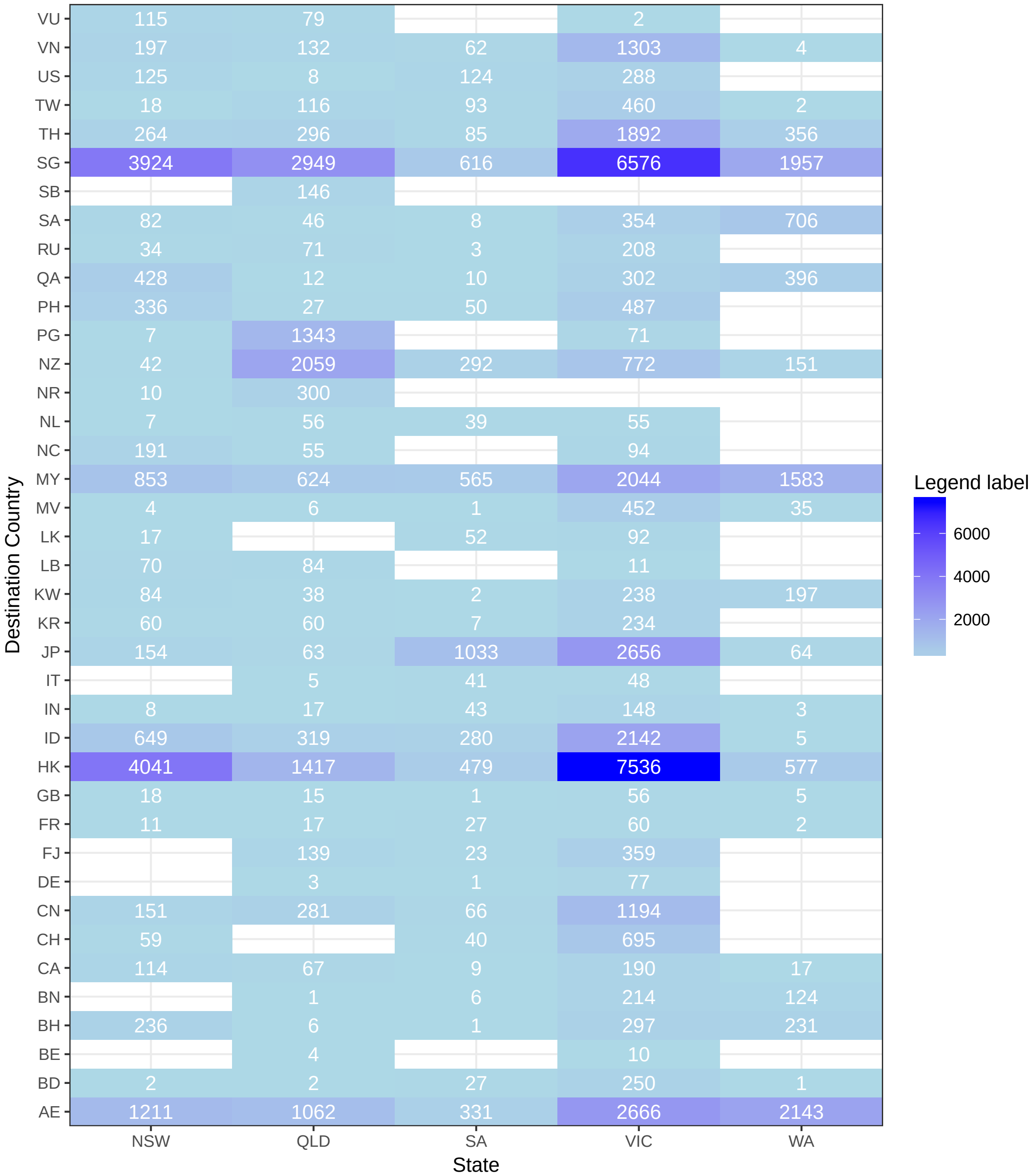

Figure A.3: Distribution of consignment counts by region and destination country for all countries with 100 or more consignments, and the largest five states by consignment count.

Figure A.4 shows the distribution of consignment counts by state and destination country for all countries with 100 or more consignments and the largest five states by consignment count and for consignments of more than 6 product classes. The combinations are dominated by consignments from Queensland to Papua New Guinea, New South Wales to Singapore (and some to Hong Kong), and Victoria to Singapore with some to Thailand.

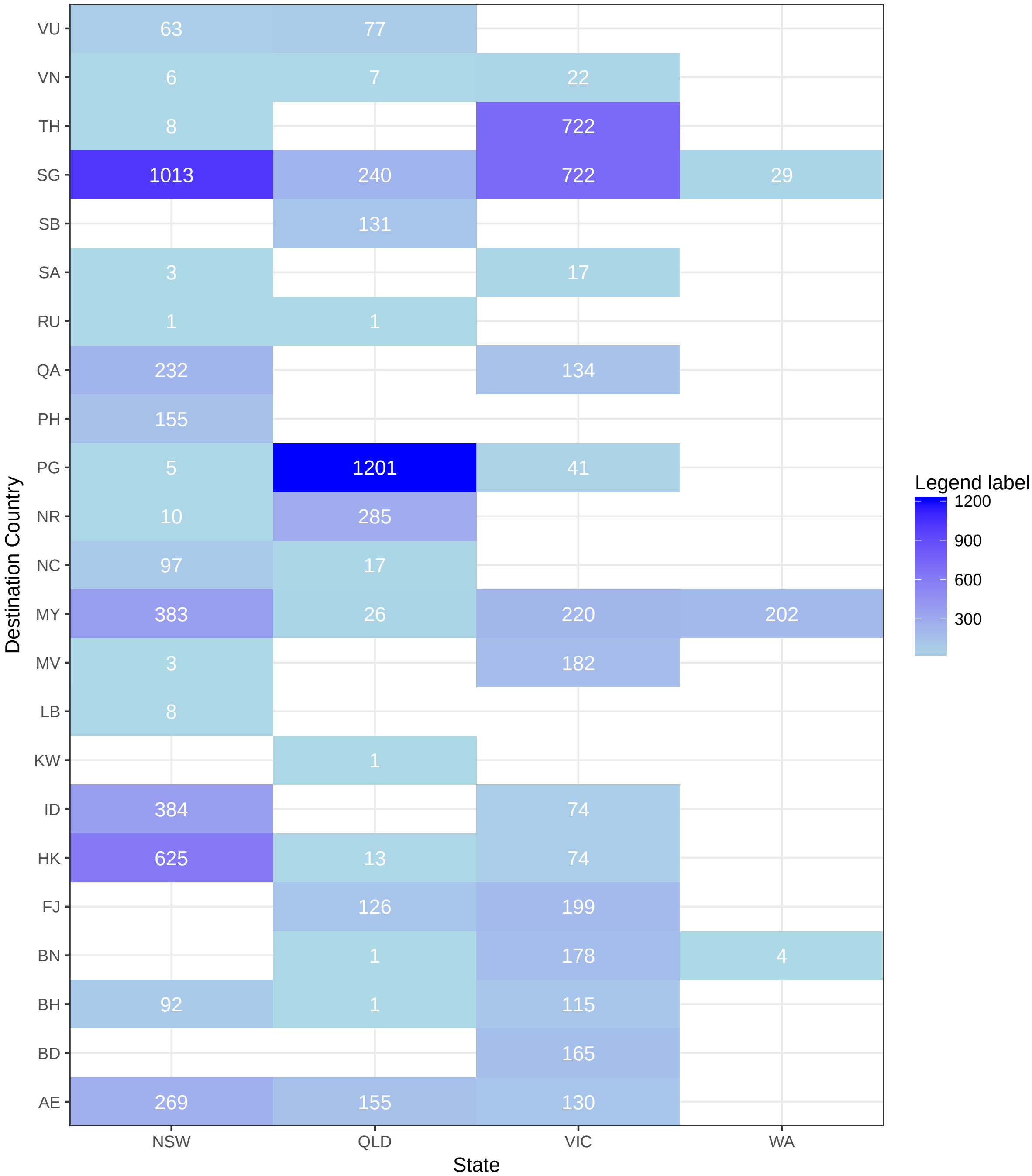

Figure A.4: Distribution of consignment counts by region and destination country for all consignments with more than six different classes, countries with 100 or more consignments, and the largest five states by consignment count.

Figure A.5 shows a summary of the pairwise combinations of the product classes for all products that appear in at least 5 consignments and for which the maximum occurrence correlation with any other product is no smaller than 0.4, and for which the adjusted p-value is no higher than 0.001. A brief explanation follows. I converted the 75000 records to a binary matrix with 75000 rows and 107 columns, the latter representing the product classes. Each cell held a 1 if the corresponding consignment included one or more items from the product class, and 0 otherwise. I then computed the correlation matrix of the columns, which can be interpreted as a measure of co-occurrence of the product classes. I also computed a matrix of p-values against the null hypothesis that the correlation was zero. I corrected the p-value matrix using Holm's algorithm (Holm, 1979). Then, the figure provides dots at only those correlations that are (i) greater than 0.4 and (ii) statistically significant at an (adjusted) size of 0.001. The area and the intensity of the dots both report the absolute value of the correlation coefficient, and the colour shows the sign (blue is positive, red is negative).

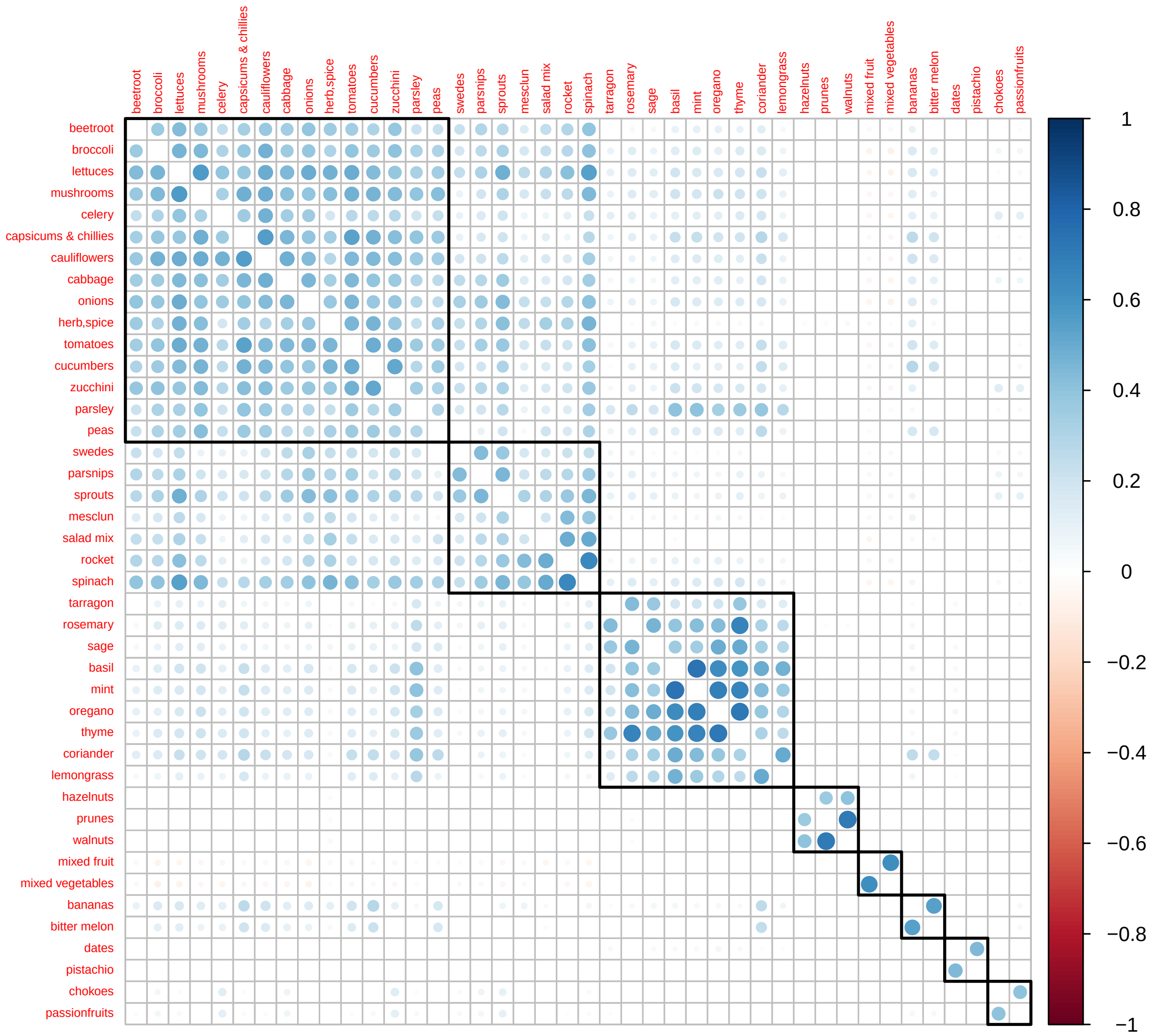

Figure A.5: Matrix of correlations between appearances of different product classes. Pairs with high correlation denote classes that are more likely to appear together.

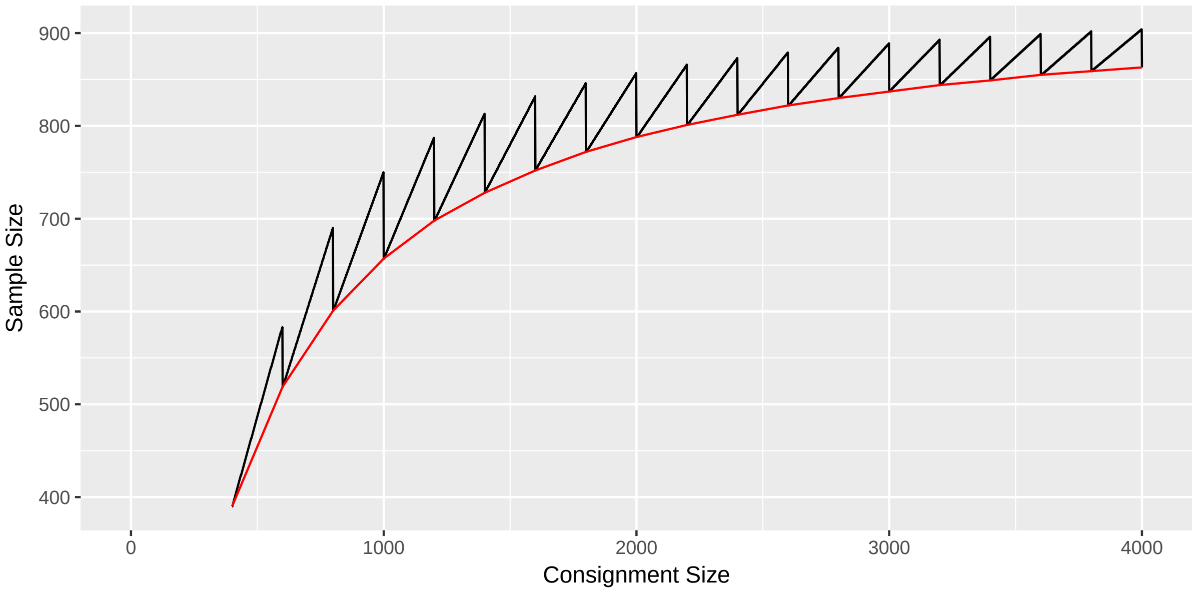

Figure A.6: The necessary sample size (y-axis) to achieve nominal probability (95%) of detecting contamination at 0.5% against the consignment size (x-axis) when a single fail is permitted.

Appendix B

Product Classes

Table B.1: Tabulation of products and classes by year (2014 / 2015) and RFP origin (EXDOC / PEMS).

Goods		**Origin**		**Year**	
Product	Class	EXDOC	PEMS	2014	2015
achacha	achacha	95	0	40	55
alfalfa	sprouts	8778	133	4753	1826
alfalfa sprouts	sprouts	603	94	390	221
alfalfa with broccoli sprouts	sprouts	1	0	0	1
alfalfa,snow pea & bean mix sprouts	sprouts	7	0	1	0
almond fruit	almond fruit	26	0	17	3
almond nuts	nuts	4	199	141	62
apple dried	dried fruit	8	0	6	2
apples	apples,pears	2569	92	1311	589
apricots	stone fruit	1400	87	719	265
apricots dried	dried fruit	11	0	9	2
artichokes - globe	globe artichokes	451	94	310	103
artichokes - jerusalem	jerusalem artichokes	241	16	112	26
asparagus	asparagus	5502	93	2905	310
avocadoes	avocadoes	3173	141	1563	603
bananas	bananas	337	0	175	69
basil	basil	396	11	187	123
bean sprout mix	sprouts	232	0	119	46
bean sprouts - mung beans	sprouts	46	0	16	10
beans	beans	900	18	496	172
beans - broad	beans	7	0	3	0
beans - flat	beans	36	0	26	9
beans - round	beans	1204	0	704	103
beans - sprouted	sprouts	146	0	90	31
beetroot	beetroot	2923	305	1764	869
bitter melon	bitter melon	117	0	58	10
blackberries	blackberries	13	4	9	2
blood limes	citrus	1	0	1	0
blueberries	blueberries	1244	16	639	175
bok choy	choy	280	0	177	68
broad beans	beans	0	7	0	7
brocco flower	broccoli	2	0	2	0
broccoli	broccoli	7891	345	4319	1809
broccoli sprouts	sprouts	4	0	4	0
broccolini	broccoli	1376	151	762	395
brussel sprouts	cabbage	2280	209	1278	724
cabbage	cabbage	26	17	15	21
cabbages	cabbage	2018	71	1053	500
cabbages - chinese	cabbage	456	9	199	88
cabbages - red	cabbage	468	1	199	102

Table B.1: *(continued)*

Goods		Origin		Year	
Product	Class	EXDOC	PEMS	2014	2015
cabbages - wombok	cabbage	950	0	572	173
capsicums	capsicums & chillies	1539	189	1009	457
capsicums - green	capsicums & chillies	832	0	391	127
capsicums - red	capsicums & chillies	1014	0	494	135
capsicums - yellow	capsicums & chillies	339	0	144	25
carambola	carambola	7	0	7	0
carrots	carrots	12780	248	6958	2964
cauliflowers	cauliflowers	3147	203	1763	732
celeriac	celeriac	576	84	359	149
celery	celery	4568	174	2414	1228
chard	silverbeet	312	30	207	61
chard - red	silverbeet	2	0	0	0
cherries	cherries	5085	209	2961	1344
chervil	chervil	84	3	35	14
chestnut fruit	chestnut	5	0	4	0
chickpeas	chickpeas	3	5	4	4
chicory	chicory	96	2	57	17
chicory radicchio	chicory	29	0	23	1
chillies	capsicums & chillies	663	2	382	133
chinese broccoli	choy	7	0	7	0
chinese vegetables	chinese vegetables	73	0	30	28
chives	onions	196	6	102	43
chokoes	chokoes	94	0	52	10
cinnamon - ground	herb,spice	2	2	4	0
coriander	coriander	405	1	207	108
corn	corn	1837	5	923	476
courgettes	zucchini	1	1	2	0
cranberries dried	dried fruit	5	0	0	5
cress - curley	cress	1	0	0	1
cucumbers	cucumbers	2162	123	1135	520
cumin seed	herb,spice	4	0	1	3
currants	currants	5	2	4	3
currants - red	currants	1	1	2	0
currants dried	dried fruit	24	1	14	10
curry leaves	herb,spice	6	0	0	6
custard apples	custard apples	520	17	271	222
dates	dates	10	0	8	0
dates dried	dried fruit	25	2	14	8
dill	dill	201	0	102	30
dragon fruit	dragon fruit	27	0	19	8

Table B.1: *(continued)*

Goods		Origin		Year	
Product	Class	EXDOC	PEMS	2014	2015
edible flowers	edible flowers	158	0	78	26
eggplant	eggplant	1079	8	538	276
endive	chicory	357	3	214	58
fennel	fennel	1625	211	975	496
fennel seed	herb,spice	1	1	2	0
figs	figs	73	27	56	38
figs dried	dried fruit	10	0	6	4
finger lime	citrus	70	0	38	26
flowers - edible	edible flowers	345	46	212	122
frissee	chicory	2	0	2	0
fruit - mixed	mixed fruit	2632	0	1356	722
galangal	galangal	2	0	2	0
garden cress	cress	56	11	44	0
garden cress micro plants	cress	58	0	32	26
garlic	garlic	798	14	411	172
ginger	ginger	370	0	198	68
grapefruit	citrus	706	34	344	146
grapes	grapes	15587	1339	7838	8658
grapes - crimson seedless	grapes	129	233	0	362
grapes - green	grapes	150	0	87	49
grapes - red	grapes	182	0	109	58
grapes - red globe	grapes	7	11	0	18
grapes - thompson seedless	grapes	87	124	0	211
guava	guava	3	0	2	1
hazelnuts	hazelnuts	5	2	3	4
herbs	herb,spice	1641	150	1023	331
herbs - mixed	herb,spice	1818	159	1015	416
honeydew melons	melons	3846	255	2098	1172
horseradish	horseradish	16	2	7	1
jujube date	dates	85	0	17	68
kaffir lime leaves	kaffir lime leaves	1	0	0	1
kale	cabbage	1073	113	665	497
kiwi fruit	kiwifruits	486	1	285	156
kiwifruits	kiwifruits	1150	32	642	254
kohl rabi	cabbage	45	11	30	19
kumera	sweet potato	53	0	7	46
kumquats	citrus	1	0	1	0
leeks	onions	2731	233	1469	757
lemongrass	lemongrass	108	0	51	16
lemons	citrus	1630	62	866	330

Table B.1: *(continued)*

Goods		**Origin**		**Year**	
Product	Class	EXDOC	PEMS	2014	2015
lettuce mix	lettuces	711	83	387	261
lettuces	lettuces	8812	747	5193	2137
limes	citrus	883	5	493	263
longan	longan	18	0	6	12
lychees	lychees	523	6	223	223
mache	mache	2	0	1	1
mandarins	citrus	4437	222	2291	572
mandarins - daisy	citrus	1	0	0	0
mandarins - murcott	citrus	472	1	327	1
mangoes	mangoes	4329	72	2027	1312
mangoes - keitt	mangoes	17	0	5	12
mangoes - kensington pride	mangoes	22	0	11	0
mangoes - r2e2	mangoes	2	0	1	0
mangoes dried	dried fruit	12	0	7	5
marjoram	marjoram	37	0	26	9
mesculan mix	mesclun	2209	48	1229	505
mint	mint	291	2	141	94
mixed dried fruit	dried fruit	13	0	8	2
mixed sultanas, raisins and currants	dried fruit	2	0	2	0
mizuna	mizuna	842	10	469	149
mungbeans - sprouted	sprouts	84	1	50	11
muscatels dried	dried fruit	2	0	0	0
mushroom growing substrate	nursery substrate	25	0	15	10
mushroom spawn	nursery substrate	1	0	0	1
mushrooms	mushrooms	3902	308	2302	903
mustard cress	cress	4	0	3	0
nashi pears	apples,pears	378	1	170	74
nectarines	stone fruit	4782	317	2445	1673
okra	okra	38	0	30	7
olives	olives	1	0	1	0
onion sprouts	sprouts	3	2	0	4
onions	onions	2231	217	1226	633
onions - brown	onions	833	4	377	284
onions - cream gold	onions	1069	0	620	263
onions - red	onions	1922	3	1063	432
onions - white	onions	761	3	412	179
oranges	citrus	11359	1669	6804	2024
oranges - lane late navel	citrus	5	2	5	2
oranges - navel	citrus	293	107	146	103
oranges - valencia	citrus	44	25	29	21

Table B.1: *(continued)*

Goods		Origin		Year	
Product	Class	EXDOC	PEMS	2014	2015
oranges - washington navel	citrus	2	193	2	193
oregano	oregano	223	0	108	74
oregano - ground	herb,spice	3	9	7	5
oregano leaves - dried	herb,spice	2	0	1	1
pak choy	choy	212	0	100	75
papaya	papaw	39	0	28	3
parsley	parsley	1148	187	662	377
parsley - dried	herb,spice	2	11	7	6
parsnips	parsnips	2460	127	1333	543
passionfruits	passionfruits	125	0	60	28
paw paws	papaw	28	0	7	13
pea shoots	shoots	24	0	7	10
peaches	stone fruit	5035	286	2433	1932
pears	apples,pears	3649	886	2410	1270
peas	peas	347	34	223	47
peat moss	nursery substrate	18	0	15	3
persimmons	persimmons	795	5	443	291
pineapples	pineapples	78	0	29	23
pistachio fruit	pistachio	59	0	11	48
plumcotes	stone fruit	6	0	4	2
plums	stone fruit	3263	137	1676	1512
pomegranates	pomegranates	135	8	64	63
potatoes	potatoes	8983	177	4601	2196
potatoes - red	potatoes	43	2	35	5
prickly pears	prickly pears	5	0	4	1
prunes	prunes	17	0	11	6
pumpkins	pumpkins	4623	13	2401	1085
pumpkins - butternut	pumpkins	1600	8	872	341
quinces	quinces	37	1	15	15
radish - sprouted	sprouts	20	0	0	18
radishes	radishes	821	133	465	265
raisins dried	dried fruit	69	78	36	105
rambutans	rambutans	1	0	1	0
raspberries	raspberries	65	3	43	8
rhubarb	rhubarb	852	92	515	236
rockett	rocket	3725	0	2088	656
rockmelons	melons	7597	222	3934	2310
rolled oats	oats	5	24	13	16
rosemary	rosemary	204	8	86	60
sage	sage	111	2	43	34

Table B.1: *(continued)*

Goods		Origin		Year	
Product	Class	EXDOC	PEMS	2014	2015
salad mix	salad mix	6585	459	3854	1341
seed potato	seed potato	60	2	33	26
shallots	onions	654	3	339	159
silverbeet	silverbeet	666	1	325	144
snow pea sprouts	sprouts	428	74	228	150
snowpeas	peas	1222	62	657	260
sorrel	sorrel	5	0	3	0
spinach	spinach	5942	411	3431	1393
spring onions	onions	399	58	206	95
squash	squash	1513	3	787	306
strawberries	strawberries	3486	170	2097	391
sultanas dried	dried fruit	213	10	103	53
swedes	swedes	1511	90	897	348
sweet potatoes	sweet potato	1832	112	997	526
sweetcorn	corn	1057	0	554	211
tamarillos	tamarillos	3	0	0	1
tangelos	citrus	204	27	104	29
tangerines	citrus	8	0	2	0
tangors	citrus	10	0	4	0
tarragon	tarragon	83	5	48	19
tatsoi	choy	84	2	35	33
thyme	thyme	338	7	161	103
tomatoes	tomatoes	6132	208	3308	1419
truffles	truffles	31	0	18	0
truffles - black	truffles	19	0	12	0
tumeric	tumeric	17	0	1	0
turnips	turnips	1138	159	671	352
vegetables - mixed	mixed vegetables	3472	0	1811	988
walnuts	walnuts	10	1	6	5
watercress	cress	61	0	30	11
watermelons	melons	2475	13	1296	638
witloof	chicory	1386	154	844	350
zucchini	zucchini	3709	159	2058	853

Appendix C

Derivation of Mixed-Lines Contamination Results

C.1 Two Heterogeneous Lines

I now prove the conjecture set out in Section 5.4, namely that if proportional allocation is applied within any pair of lines, then the sensitivity of the inspection is at least as good as nominal regardless of the difference in the contamination levels of the lines.

Put another way, if the joint contamination rate of the two lines is nominal at e.g. 0.5%, and inspection is perfect then a proportionally allocated random sample of 600 units will have *at least* 95% probability of detecting the contamination. I will show that the assumption that the contamination rate of the lines is identical at (e.g.) 0.5% is conservative, and if the rates of the two lines differs then proportional allocation leads to performance that is nominal at 95% sensitivity, *or better*.

As a demonstration of the claim, Figure C.1 shows the effect of equal allocation of 600 sampling units between two identically sized lines of 15000 units each. The curve exceeds the nominal sensitivity at $p_1 = 0.5\%$, is increasingly above the nominal sensitivity otherwise, and is symmetric in p_1. The difference is too small to be of operational interest, but nonetheless this shows that the nominal sensitivity is uniformly exceeded.

The proof is as follows. Consider any pair of lines labelled 1 and 2, with total number of units N_1 and N_2 respectively.

Assume that the lines may be heterogeneous but we do not know whether this is true, nor do we know which would have the higher contamination rate.

Assume that we allocate inspection efforts to the two lines proportionally to their volume, that is, let the sample sizes n_1 and n_2 be computed as a constant fraction $f, (0 < f \leq 1)$ of the line volumes,

$$n_1 = fN_1;\ n_2 = fN_2. \tag{C.1}$$

The lines may have different inherent rates of contamination p_1 and p_2, with the constraint that the joint contamination is nominal at the fixed value of p, e.g., 0.5%. As a consequence of this constraint, we can say that

$$p_2 = \frac{pN - p_1N_1}{N_2} \tag{C.2}$$

Then the desired sensitivity for the surveillance s, set at e.g. $s = 0.95$ (95%, equivalent to 5% size), is what we choose as the desired probability of no detected contamination across the two lines if the overall contamination rate is at nominal p:

$$\begin{aligned}
s &= 1 - (1 - p_1)^{n_1} \times (1 - p_2)^{n_2} && \text{(C.3)}\\
&= 1 - (1 - p_1)^{fN_1} \times (1 - p_2)^{fN_2} \qquad \text{(by C.1)} && \text{(C.4)}\\
&= 1 - (1 - p_1)^{fN_1} \times \left(1 - \frac{pN - p_1N_1}{N_2}\right)^{fN_2} \qquad \text{(by C.2)} && \text{(C.5)}
\end{aligned}$$

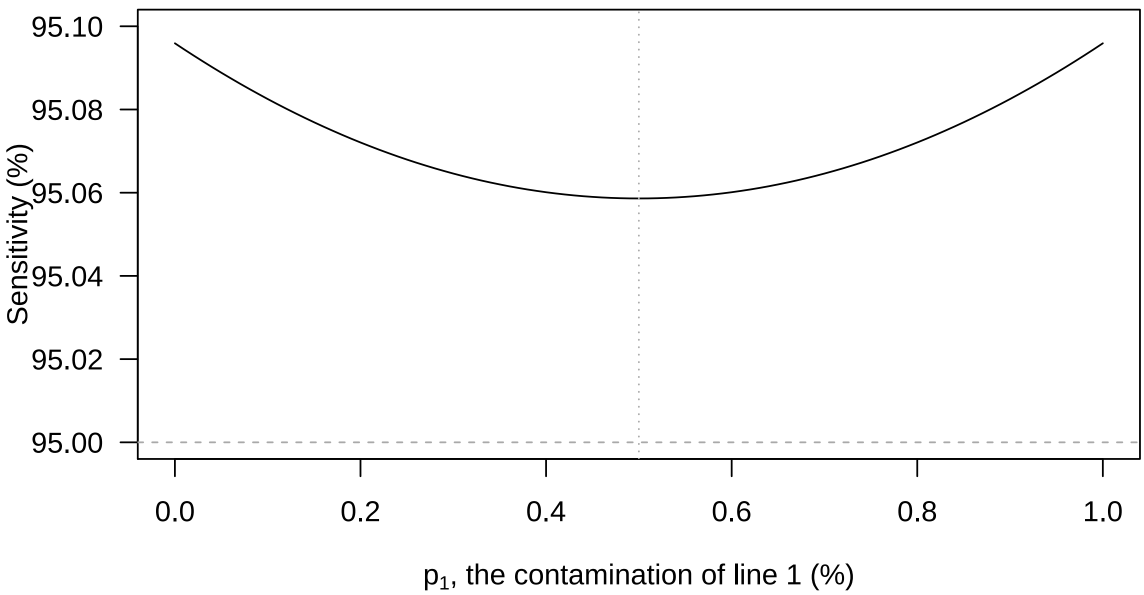

Figure C.1: The effect upon the size (y-axis) of the contamination of line 1 (x-axis) for proportional allocation of 600 sampling units among the product lines. Note, the nominal size is 5% (dashed grey line) and the overall contamination p is set at 0.5%.

Now subtract both sides from 1, so that we have the size instead of the sensitivity, because the size is easier to manipulate in this setting.

$$1 - s = (1 - p_1)^{fN_1} \times \left(1 - \frac{pN - p_1 N_1}{N_2}\right)^{fN_2} \tag{C.6}$$

We now want to prove that $p_1 = p_2 = p$ maximizes the size, which is equivalent to minimizing the sensitivity. We take the log of both sides, differentiate with respect to p_1, differentiate again with respect to p_1, and evaluate these first and second derivatives at $p_1 = p$. *If the conjecture is true then the first derivative will be 0 and the second derivative will be negative.* This plays out as follows.
The log of $1 - s$ is:

$$\log(1 - s) = fN_1 \log(1 - p_1) + fN_2 \log\left(1 - \frac{p(N_1 + N_2) - p_1 N_1}{N_2}\right) \tag{C.7}$$

The first derivative of $\log(1 - s)$ with respect to p_1 follows (Wolfram|Alpha, 2017a).

$$\frac{\partial \log(1 - s)}{\partial p_1} = -\frac{fN_1(N_1 + N_2)(p - p_1)}{(p_1 - 1)(N_1(p_1 - p) + N_2(1 - p))}, \tag{C.8}$$

which is 0 *only* when evaluated at $p_1 = p$.

This verifies that the inflection point of the size function is achieved only at $p_1 = p$, which is the point at which the lines are homogeneous — the contamination is constant throughout both lines.

We now verify that this sole inflection point is a maximum. The second derivative of $\log(1 - s)$ with respect to p_1 follows (Wolfram|Alpha, 2017b).

$$\frac{\partial^2 \log(1 - s)}{\partial p_1^2} = -\frac{fN_1(N_1 + N_2)(N_1(p - p_1)^2 + N_2(p - 1)^2)}{(p_1 - 1)^2(N_1(p_1 - p) + N_2(1 - p))^2} \tag{C.9}$$

Evaluated at $p_1 = p$,

$$\left.\frac{\partial^2 \log(1 - s)}{\partial p_1^2}\right|_{p_1 = p} = -\frac{fN_1(N_1 + N_2)}{N_2(p - 1)^2} \tag{C.10}$$

Equation C.10 is always less than 0 because N_1, N_2, and f are all non-negative. Therefore the first derivative is decreasing through zero, and the size evaluated at $p_1 = p$ is a maximum, so the sensitivity evaluated at $p_1 = p$ is a minimum. This completes the proof that treating two heterogeneous mixed lines as though they were homogeneous is conservative under proportional allocation.

The proof shows that under proportional sample allocation, treating the combination of two lines as though they were a single line achieves the required sensitivity. We now generalize the proof to include an arbitrary number of mixed heterogeneous lines.

C.2 Many Heterogeneous Lines

Assume that we have L such lines with volumes $N_1, \ldots N_L$ and contamination rates $p_1, \ldots, p_L$. Allocate the sample of 600 units to each line proportionally to its volume, as prescribed above, so that $n_1/N_1 = \ldots = n_L/N_L = f$.

Now consider any pair of lines, e.g. a and b. We know from the above proof that treating the lines as a single line is conservative under proportional allocation. So, we can treat this pair of lines as a single line ab for the purposes of sampling. Because we allocated the sample to a and b proportionally, we have also allocated the sample to ab proportionally, that is, $n_{ab}/N_{ab} = f$. We know from our proof that sampling line ab under proportional allocation achieves our required sensitivity for lines a and b.

Next, merge the new line ab with any other line c. By the same logic, $n_{abc}/N_{abc} = f$, so the nominal sensitivity is achieved again. We can continue the process until all L lines are merged. Hence, sampling an arbitrary number of mixed lines by proportionally allocating the usual number of units by volume will achieve the nominal sensitivity.

C.3 Operational Caveat

This proof relies on the assumption of exact proportional allocation to lines by their volumes. Lines can have arbitrary volumes, so it cannot be guaranteed that exact proportional allocation can be achieved. A simple remedy that guarantees that nominal sensitivity can be exceeded is to round the number of samples allocated to each line *up* to the nearest whole number.