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NOVEL METHODS FOR DOSE-RESPONSE META-ANALYSIS

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NOVEL METHODS FOR DOSE-RESPONSE META-ANALYSIS

THESIS FOR DOCTORAL DEGREE (Ph.D.)

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*“The function of the expert reviewer is not to be more right than other people,
but to be wrong for more sophisticated reasons.”*

—Iain Chalmers and Douglas G. Altman

Systematic Reviews, 1995

Abstract

Dose–response meta-analysis is a statistical procedure for combining and contrasting the evidence on the association between a continuous exposure and the risk of a health outcome. Several papers refined selected aspects of the methodology, such as implementation of flexible strategies and extensions to multivariate meta-analysis. However, there were still several relevant questions that needed to be addressed. This thesis aims to address these issues by developing and implementing new strategies and ad-hoc measures (Paper I), including tools for evaluating the goodness-of-fit (Paper II), a new measure for quantifying the impact of heterogeneity (Paper III), a strategy to deal with differences in the exposure range across studies (Paper IV), and a one-stage approach to estimate complex models without excluding relevant studies (Paper V).

In Paper I, we described the implementation of the main aspects of the methodology in the `dosresmeta` R package available on CRAN. Dedicated functions were written to facilitate specific tasks such as definition of the design matrix and prediction of the pooled results. We illustrated how to estimate both linear and non-linear curves, conduct test of hypotheses, and present the results in a tabular and graphical format using summarized data on alcohol intake and colorectal cancer risk.

In Paper II, we discussed how to evaluate the goodness-of-fit. The proposed solutions consist of descriptive measures to summarize the agreement between fitted and observed data (the deviance and the coefficient of determination), and graphical tools to visualize the fit of the model (decorrelated residuals-versus-exposure plot). A reanalysis of two published meta-analyses exemplified how these tools can improve the practice of quantitative synthesis of aggregated dose–response data.

In Paper III, we proposed and characterized a new measure, R_b , to quantify the proportion of the variance of the pooled estimate attributable to the between-study heterogeneity. Contrary to the available measures of heterogeneity, R_b does not make any assumption about the distribution of the within-study error variances, nor does it require specification of a typical value for these quantities. The performance of the proposed measure was evaluated in an extensive simulation study. We demonstrated how to present and interpret the R_b re-analyzing three published meta-analyses.

In Paper IV, we extended a point-wise approach to dose–response meta-analysis of aggregated data. The strategy consists of combining predicted relative risks for a fine grid of exposure values based on potentially different dose–response models. A point-wise approach can improve the flexibility in modeling the study-specific curves and may limit the impact of extrapolation by predicting the study-specific relative risk based on the observed exposure range. We illustrated the methodology using both individual and aggregated participant data.

In Paper V, we formalized a one-stage approach for dose–response meta-analysis in terms of a linear mixed model. We explained the main aspects of the methodology and how to extend the measures typically presented in a two-stage analysis. Using both hypothetical and real data, we showed how the one-stage approach can facilitate investigation of the impact of heterogeneity over the exposure range, model comparison, and prediction of individual dose–response associations. The main advantage is that flexible curves can be estimated regardless of the number of data-points in the individual analyses.

In conclusion, the methods presented in this thesis enrich the set of tools available for applying dose–response meta-analyses and for addressing specific questions including goodness-of-fit evaluation (Paper II) and quantification of heterogeneity (Paper III). In addition, we presented alternative models for pooling results in case of heterogeneous exposure range (Paper IV) and for estimating complex models without excluding relevant studies (Paper V). The proposed methods have been illustrated using real data and implemented in the `dosresmeta` and `hetmeta` R packages available on CRAN (Paper I).

List of publications

- I. Alessio Crippa, and Nicola Orsini
Multivariate dose–response meta-analysis: the dosresmeta R Package
Journal of Statistical Software, Code Snippets 2016; 72(1), 1–15
- II. Andrea Discacciati, Alessio Crippa, and Nicola Orsini
Goodness of fit tools for dose–response meta-analysis of binary outcomes
Research Synthesis Methods 2015
- III. Alessio Crippa, Polyna Khudyakov, Molin Wang, Nicola Orsini, and Donna Spiegelman
A new measure of between-studies heterogeneity in meta-analysis
Statistics in medicine 2016; 35(21), 3661–75
- IV. Alessio Crippa, Ilias Thomas, and Nicola Orsini
A pointwise approach to dose-response meta-analysis of aggregated data
Manuscript 2018
- V. Alessio Crippa, Andrea Discacciati, Matteo Bottai, Alicja Wolk, and Nicola Orsini
One-stage dose–response meta-analysis for aggregated data
Manuscript 2018

The articles will be referred to in the text by their Roman numerals, and are reproduced in full at the end of the thesis.

Related publications

- Ehimen C. Aneni, Alessio Crippa, Chukwuemeka U. Osondu, Javier Valero-Elizondo, Adnan Younus, Khurram Nasir, and Emir Veledar
Estimates of Mortality Benefit From Ideal Cardiovascular Health Metrics: A Dose Response Meta-Analysis
Journal of the American Heart Association 2017 Dec 1;6(12):e006904.
- Alessio Crippa, Susanna C. Larsson, Andrea Discacciati, Alicja Wolk, and Nicola Orsini
Red and processed meat consumption and risk of bladder cancer: a dose–response meta-analysis of epidemiological studies
European journal of nutrition 2016, 1–13
- Alessio Crippa, Susanna C. Larsson, Andrea Discacciati, Alicja Wolk, and Nicola Orsini
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Diabetologia 2016, 1–19
- Marco Vinceti, Tommaso Filippini, Alessio Crippa, Agnès de Sesmaisons, Lauren A. Wise, and Nicola Orsini
Meta-Analysis of Potassium Intake and the Risk of Stroke
Journal of the American Heart Association 2016, 5(10), e004210
- Alessio Crippa, and Nicola Orsini
Dose–response meta-analysis of differences in means
BMC medical research methodology 2016, 16(1), 91
- Emir Veledar, Alessio Crippa, Chukwuemeka U. Osondu, Adnan Younus, and Khurram Nasir
Letter to Editor: Ideal cardiovascular health metrics and risk of cardiovascular disease or mortality
International journal of cardiology 2016, 222, 737

- Alessio Crippa, Andrea Discacciati, Nicola Orsini, and Viktor Oskarsson
Letter: coffee consumption and gallstone disease—a cautionary note on the assignment of exposure values in dose–response meta-analyses
Alimentary Pharmacology & Therapeutics 2016, 43(1), 166-167
- Susanna C. Larsson, Alessio Crippa, Nicola Orsini, Alicja Wolk, and Karl Michaëlsson
Milk consumption and mortality from all causes, cardiovascular disease, and cancer: a systematic review and meta-analysis
Nutrients 2016, 7(9), 7749-7763
- Daniela Di Giuseppe, Alessio Crippa, Nicola Orsini, and Alicja Wolk
Fish consumption and risk of rheumatoid arthritis: a dose-response meta-analysis
Arthritis research & therapy 2014, 16(5), 446
- Alessio Crippa, Andrea Discacciati, Susanna C. Larsson, Alicja Wolk, and Nicola Orsini
Coffee consumption and mortality from all causes, cardiovascular disease, and cancer: a dose–response meta-analysis
American journal of epidemiology 2014, 180(8), 763-775

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List of abbreviations

AIC	Akaike Information Criterion
CI	Confidence Interval
CS	Cubic Splines
df	Degrees of Freedom
GLS	Generalized Least Squares
GRSS	Generalized Residual Sum of Squares
GTSS	Generalized Total Sum of Squares
FP2	Second-degree Fractional Polynomials
logRR	log-Relative Risk
RCS	Restricted Cubic Splines
R^2	Coefficient of Determination
RR	Relative Risk
WLS	Weighted Least Squares

Chapter 1

Introduction

A single experiment can hardly provide a definitive answer to a scientific question. Science is oftentimes referred to as a cumulative process where results from many studies, aiming to address the common question of interest, contribute to create and update the scientific evidence. In the cumulative paradigm, meta-analysis is the statistical methodology to combine and compare the current evidence in the field. This process lies at the heart of the concept of evidence-based medicine, and plays a major role in informing policy and practice.

Epidemiological studies often assess whether the occurrence of a health outcome (e.g. mortality, incidence of a disease) varies according to a quantitative exposure (e.g. amount of physical activity, alcohol intake). The quantitative exposure is frequently divided in intervals and the results are expressed in a tabular format as relative risks for different exposure groups. A high versus low meta-analysis contrasts the relative risks for the highest exposure category compared to the lower one. This approach, however, discards the results for intermediate categories and thus provides only a limited picture. The information of the quantitative exposure is also lost and the estimates being compared may be associated to different exposure values.

A dose-response meta-analysis, instead, has the potential to be more informative and powerful since it uses the whole available information to estimate the dose-response association. Because the estimates depend on the same reference group, it is not possible to regress the relative risks on the assigned dose using ordinary least square. Greenland and Longnecker described in their seminal paper in 1992 how to reconstruct the correlation within set of relative risks and incorporate it in the dose-response analysis using generalized least square regression. Since then, the number of published dose-response meta-analysis has rapidly increased in many fields of application including oncology, public health, environmental sciences, nutrition, endocrinology, and internal medicine. Additional papers refined selected aspects of the proposed methodology, mainly focusing on the implementation of flexible strategies in modeling non-linear associations and incorporating the advances of multivariate meta-analysis. However, there were still several relevant questions that needed to be addressed such as how to assess the goodness-of-fit (Paper II), how to quantify the impact of heterogeneity (Paper III), how to deal with differences in the exposure range across studies (Paper IV), and how to estimate complex models without excluding relevant studies (Paper V).

This thesis aims to address these issues by developing and implementing new strategies and ad-hoc measures (Paper I). The proposed methodologies are demonstrated reanalyzing published meta-analyses and are implemented in user friendly packages written in the free and open source R language, to bridge the gap between theory and application.

Chapter 2

Background

2.1 Meta-analysis

Relevant research questions are typically addressed by independent investigators in multiple studies. The sampling error and possibly differences in the investigations will inevitably produce diverse results, sometimes even conflicting. Evidence-based medicine requires a synthesis of the available evidence to optimize the decision-making process (Haidich, 2010).

Meta-analysis, or more generally quantitative review synthesis, is the statistical methodology for integrating and synthesizing the information arising from multiple studies (Borenstein *et al.*, 2009). Using appropriate statistical models, quantitative reviews contrast and pool results in the hope of identifying similarities or explain differences across study findings. Meta-analysis represents the state of the art for systematically reviewing the evidence, as indicated by the increasing number of published meta-analyses over the last 40 years (figure 2.1).

The classical approach for meta-analysis consists of a weighted average of the study-specific results or estimates. A fixed-effect model for meta-analysis assumes that all the studies estimate a single common parameter (Rice *et al.*, 2017). The hypothesis of homogeneity of the estimates is rarely applicable in biomedical and social sciences where studies typically differ in terms of design, disease classification, exposure measurement, and implemented statistical analyses (Colditz *et al.*, 1995). In such cases, heterogeneity across estimates is expected and should be considered in the analysis (Higgins, 2008). If the parameters estimated in the studies are not identical but similar, a random-effects models can be used to identify those similarities or to explain the observed heterogeneity (Higgins *et al.*, 2009).

2.1.1 Random-effects meta-analysis

In a meta-analysis of I studies indexed by $i = 1, \dots, I$, we denote $\hat{\beta}_i$ the estimate of an effect of interest (effect size) in the i -th study. A random-effects model for meta-analysis can be written as

$$\hat{\beta}_i = \beta + b_i + \varepsilon_i \quad (2.1)$$

where β is the underlying mean effect, oftentimes the main parameter of interest. The random-

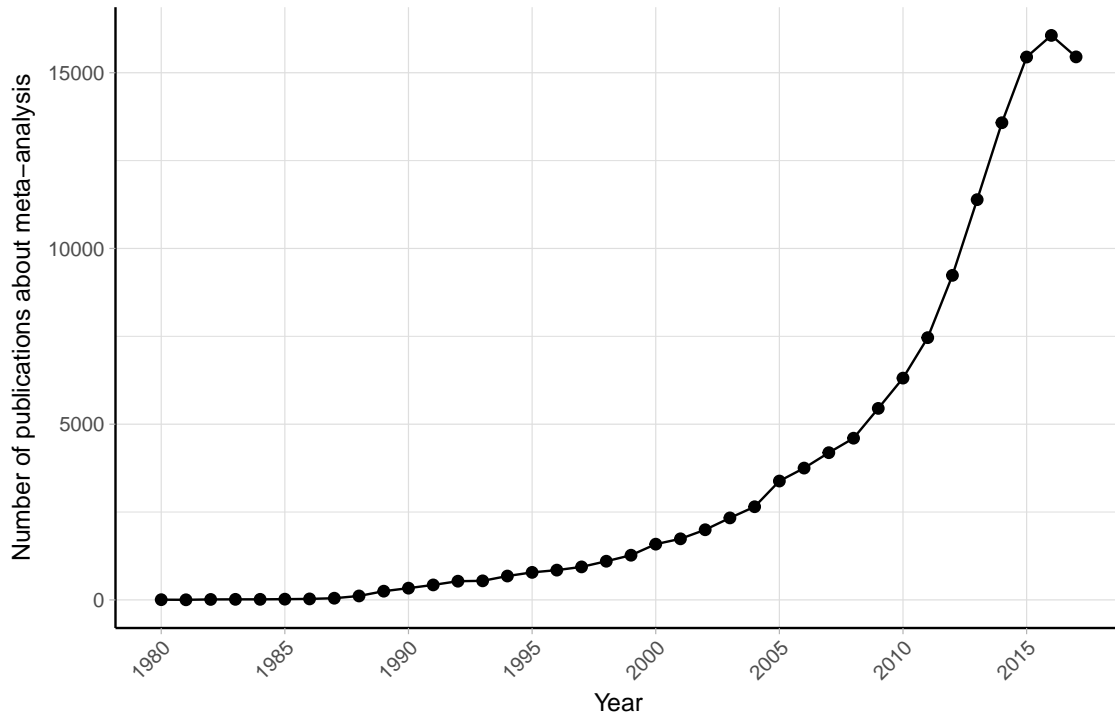


Figure 2.1: Number of publications about meta-analysis (results from Medline search using text "meta-analysis" until December 2017).

effects b_i represent the study-specific deviations from the mean effect β allowing each study to estimate a similar parameter β_i defined as $\beta + b_i$. The random effects follow a generic f distribution with mean 0 and variance equal to τ^2 , the between-studies heterogeneity. The within-study error components ε_i have also mean 0 and variance equal to \hat{v}_i , an estimate of the sampling variance of $\hat{\beta}_i$. Because the sample size in the individual investigations is often large, the uncertainty around the estimates of the sampling variance is negligible. Therefore, \hat{v}_i can be considered fixed and denoted as v_i . In addition, for the central limit theorem, $\varepsilon_i \sim \mathcal{N}(0, v_i)$, or alternatively, $\hat{\beta}_i | b_i \sim \mathcal{N}(\beta + b_i, v_i)$.

An inverse variance-weighted approach for meta-analysis estimates the mean effect β as a weighted average of the $\hat{\beta}_i$ (Whitehead and Whitehead, 1991; DerSimonian and Laird, 1986)

$$\hat{\beta} = \frac{\sum_{i=1}^I \hat{\beta}_i \hat{w}_i}{\sum_{i=1}^I \hat{w}_i} \quad (2.2)$$

$$\widehat{\text{Var}}(\hat{\beta}) = \left(\sum_{i=1}^I \hat{w}_i \right)^{-1} \quad (2.3)$$

with weights $\hat{w}_i = (v_i + \hat{\tau}^2)^{-1}$ and $\hat{\tau}^2$ being an estimate of the between-study heterogeneity.

2.1.2 Test and estimates of heterogeneity

A second parameter of interest, often overlooked, is the between-study heterogeneity, τ^2 . Focusing on the mean effect alone may provide only a limited piece of information, especially in case of heterogeneous effects (Borenstein *et al.*, 2010). Indeed, an evaluation of the extent of heterogeneity is a crucial step in determining the appropriateness of presenting a summary measure of the observed effect sizes.

Presence of heterogeneity is frequently defined as the excess in the variability of $\hat{\beta}_i$ above that expected alone by chance. A summary measure of the observed variability is represented by the Q statistic

$$Q = \sum_{i=1}^I (\hat{\beta}_i - \hat{\beta}_{fe})^2 \quad (2.4)$$

where $\hat{\beta}_{fe} = \sum_{i=1}^I \hat{\beta}_i v_i^{-2} / \sum_{i=1}^I v_i^{-2}$ is the estimate of β in a fixed-effect model. Based on this statistic, Cochran developed a test for assessing the hypothesis of homogeneity of the study-specific estimates (Cochran, 1954). Under the null hypothesis of no heterogeneity ($H_0 : \tau^2 = 0$) the Q statistic follows a χ^2 distribution with $I - 1$ degrees of freedom. A p value less than 0.10 is oftentimes used as evidence for presence of between-studies variability. It is known, however, that the test is sensible to the number of studies I failing to reject the null hypothesis even for high value of τ^2 when K is small, and contrary, is more likely to reject H_0 for negligible between-studies variation when K is big (Higgins and Thompson, 2002; Takkouche *et al.*, 1999). Therefore, failing to reject the null hypothesis does not provide evidence supporting homogeneity in the effect sizes (Biggerstaff and Tweedie, 1997). In addition, the dichotomization heterogeneous/homogeneous is not very informative, especially because heterogeneity is almost always present (Higgins, 2008).

An estimate of τ^2 , instead, directly provides information about the amount of heterogeneity and is thus the more natural measure of between-studies variability. Based on the expectation of Q , Dersimonian and Laird proposed the following estimator for τ^2 using the method of moments (DerSimonian and Laird, 1986)

$$\hat{\tau}_{DL}^2 = \max \left\{ 0, \frac{Q - (I - 1)}{\sum_{i=1}^I v_i^{-2} - \sum_{i=1}^I v_i^{-4} / \sum_{i=1}^I v_i^{-2}} \right\} \quad (2.5)$$

The moment-based estimator is one of the most popular estimators of τ^2 because it has a simple non-iterative formulation and does not require any distributional assumption for the random-effects rather than having a finite first order moment. Other common non-iterative alternatives include estimators based on the variance components (Hedges, 1983) and on methods for estimating the error variance in weighted linear models (Sidik and Jonkman, 2005). Iterative methods based on maximizing the likelihood or restricted likelihood can also be used by specifying a distributional form for the random-effects. The more conventional choice is typically a normal distribution $b_i \sim \mathcal{N}(0, \tau^2)$, which implies $\beta_i \sim \mathcal{N}(\beta, \tau^2)$ and $\hat{\beta}_i \sim \mathcal{N}(\beta + b_i, \tau^2 + v_i)$.

Although τ^2 is the more natural and appropriate measure of between-study variability, the actual value is difficult to interpret because it depends on type of effect size (e.g. log relative risk, standardized mean difference) and has no upper limit. Therefore, both evaluation of the degree (or levels) and the comparison of heterogeneity in different meta-analyses can hardly be based on the estimate of τ^2 .

2.1.3 Measures of heterogeneity

To complement the test based approach and the information provided by $\hat{\tau}^2$, measures that quantify the impact of heterogeneity have been proposed (Higgins and Thompson, 2002). Higgins et al. presented several possibilities in the simpler case where all the sampling variances v_i are equal to a fixed and known value σ^2 .

Two measures aim to estimate the ratio $\sigma^2/(\sigma^2 + \tau^2)$, namely the $H^2 = Q/(I - 1)$ that represents the excess in Q statistic relative to its degrees of freedom, and $R^2 = \text{Var}(\hat{\beta}) / \text{Var}(\hat{\beta}_{\text{FE}})$ which describes the inflation in the variability of the mean effect in a random-effects model compared with a fixed-effect model. Other measures, instead, relate the between-studies heterogeneity, τ^2 , to the marginal or unconditional variability $\tau^2 + v_i$, which is defined by the sum of within- and between-study components. These measures can be more easily interpreted as the percentage of the total variability due to heterogeneity, similar to the intraclass correlation coefficient defined for linear mixed-effects models. The ratio directly involves the within-terms v_i that again varies across the studies. Indeed, the most popular measures, namely the R_I (Takkouche *et al.*, 1999) and the I^2 (Higgins and Thompson, 2002), replaced v_i with a statistic that summarizes the observed distribution of v_i . Takkouche et al. chose

$$s_1^2 = \frac{I}{\sum_{i=1}^I v_i^{-2}} \quad (2.6)$$

that is the harmonic mean of the inverse of the sampling variances. Higgins et al., instead, described the “typical” within-study variance as

$$s_2^2 = \frac{(I - 1) \sum_{i=1}^I v_i^{-2}}{\left(\sum_{i=1}^I v_i^{-2} \right)^2 - \sum_{i=1}^I v_i^{-4}} \quad (2.7)$$

that provided a direct relationship with the Q statistic: $I^2 = (Q - (I - 1))/Q$ when τ^2 is estimated using the method of moments. Both statistics can be expressed as a percentage where 0% corresponds to no heterogeneity and increasing values imply higher levels of heterogeneity. It is known that these measures depend on precision of the study-specific estimates and tend to increase to 100% when the v_i are much smaller than the estimated τ^2 . A complementary measure is the between-studies coefficient of variation, defined as $\tau^2/|\hat{\beta}|$, that does not directly depend on the within-study variances. However, it increases quickly as $\hat{\beta}$ becomes smaller, and is not defined for $\hat{\beta} = 0$.

2.2 Categorical models for dose–response analysis

Epidemiological studies often assess the strength and direction of the association between protective or risk factors (generally referred to as exposures) and the occurrence of a health outcome. When the exposure of interest is measured on a continuous scale, the additional information on the shape of the relationship is mostly of interest. Including the continuous variable simply as covariate in the appropriate statistical model assumes that the outcome linearly depends on the covariate. Associations between variables, however, are rarely linear. If the real dose–response is in fact non-linear, estimating a linear trend will have important consequences in detecting an association (Harrell Jr, 2015).

One common approach to relax the linearity assumption is to divide the quantitative exposure in categories. This categorical approach has been frequently criticized because of severe limitations (Royston *et al.*, 2006; Greenland, 1995) including loss of information and thus power, assuming an unrealistic step function, and subjective choice in selecting cut-points. Instead, many articles presented and illustrated alternative solutions such as the use of fractional polynomials and regression splines for easily modelling non-linear relationships.

Nevertheless, a recent survey among top medical and epidemiological journals estimated that categorization occurred 86% of the times (Turner *et al.*, 2010). One possible reason is that a categorical approach facilitates the interpretation of the estimated regression coefficients and simplifies the presentation of the results in a tabular format (Orsini *et al.*, 2011a).

2.2.1 Aggregated dose–response data

In a categorical approach the quantitative exposure is divided in $J + 1$ categories. The corresponding indicator or dummy variables index by $j = 1, \dots, J$ are included in the model in place of the exposure variable. The results from such a categorical dose–response analysis are expressed as relative measures using one category (corresponding to the omitted dummy variable) as referent. Depending on the study-design and on the statistical model, the results consist of estimated odds ratios, rate ratios, or risk ratios (generally referred to as relative risks (RRs)) for the different exposure categories, possibly adjusted for potential confounders. The corresponding 95% confidence intervals $\widehat{RR}_L, \widehat{RR}_U$ provide information on the uncertainty related to the estimated regression coefficients. Additional information about the assigned dose (mean or median within exposure intervals), the number of cases and the total number of subjects or person-time usually complements the reported results. The general structure and notation for aggregated or summarized dose–response data are presented for a generic i -th study in table 2.1. The i pedix in J_i highlights that independent studies may categorized the continuous exposure using different number of categories.

The statistical model relate the effect of the exposure categories on a transformation of the mean outcome. Typically, these transformations involve the natural logarithm such as the log odds, log risk, or log rate. The estimated regression coefficients are then exponentiated for ease of interpretation but the inference is actually performed on the modelling scale. Therefore, the

Table 2.1: Aggregated results from a categorical dose–response analysis.

Exposure level	Assigned dose	Cases	n ^a	\widehat{RR}	95% CI
0	x_{i0}	c_{i0}	n_{i0}	1	—
1	x_{i1}	c_{i1}	n_{i1}	\widehat{RR}_{i1}	$\widehat{RR}_{Li1}, \widehat{RR}_{Ui1}$
\vdots	\vdots	\vdots	\vdots	\vdots	\vdots
J_i	x_{iJ_i}	c_{iJ_i}	J_{iJ_i}	\widehat{RR}_{iJ_i}	$\widehat{RR}_{LiJ_i}, \widehat{RR}_{UiJ_i}$

^a Depending on the study design, this column reports either total number of subjects or amount of person-time.

effect sizes considered in a meta-analysis of multiple aggregated dose–response data consist of the estimated log \widehat{RR} s and the corresponding standard errors that can be easily derived from the data available in table 2.1

$$\widehat{SE}(\log \widehat{RR}) = \frac{\log(\widehat{RR}_U) - \log(\widehat{RR}_L)}{2 z_{1-\alpha/2}} \quad (2.8)$$

where $z_{1-\alpha/2}$ is the $1 - \alpha/2$ quantile of a standard normal distribution, usually approximated to 1.96 for the common $\alpha = 5\%$ level.

A distinctive feature of aggregated dose–response data is the correlation among the (log) \widehat{RR} s, which arises from the fact that they are estimated using a common reference group. Each \widehat{RR} has the same baseline risk as denominator that works as comparator. If the observed baseline risk happens to be high or low just by chance, the estimated \widehat{RR} s will be also higher or lower than expected. This adds complications in guessing a trend from a categorical dose–response analysis or in directly comparing results based on different baseline categories.

2.2.2 High vs. low, categorical, and meta-regression models

A common approach for synthesizing the information from multiple aggregated dose–response data is to limit the analysis on a small portion of the available results. In particular, a high-versus-low meta-analysis focuses on the results for the highest exposure categories. By selecting only the last row of the aggregated dose–response data, the meta-analytic models discussed in section 2.1.1 are used for combining and contrasting the results, with $\hat{\beta}_i = \widehat{RR}_{iJ_i}$. A major limitation of a high- versus-low approach is that both the highest and the lowest category may be associated to a different exposure value. To limit the impact of heterogeneous category definitions, practitioners should carefully plan the analysis by selecting the \widehat{RR} s for exposure categories whose definition is more consistent across studies. If also the choice of baseline category substantially differs, the \widehat{RR} s can be re-expressed using an alternative reference category implementing dedicated methodologies Hamling *et al.* (2008).

The major limitation, however, is that only a subset of the data is analyzed, while the remaining information about intermediate exposure categories is excluded from the analysis. As a consequence, much of the information about the shape of the dose–response is lost and the

power of detecting an association may dramatically decrease (e.g. in case of a U-shape relationship). A possible remedy, although less common, is to conduct a categorical meta-analysis, which consists of separate univariate meta-analyses pooling the results from comparable exposure categories. A dose–response association is then deducted from observing the combined \widehat{RR} s for increasing dose levels. Apart from evident difficulties in identifying \widehat{RR} s for homogeneous exposure intervals in applied works, this approach does not take into account the correlations across set of log \widehat{RR} s and suffers from the same problem of guessing a trend from a categorical dose–response analysis.

An additional alternative may be the use meta-regression models Berkey *et al.* (1995), where the dummy variables for the exposure categories or transformation of the dose are included as covariates in model 2.1. The rationale would be to estimate a pooled RR s for different dose levels and to reduce the heterogeneity across study findings. Despite the quantitative exposure can be modelled using flexible tools, a meta-regression model treats the continuous predictor as a confounder. In addition, inference may be severely biased because the described approach fails to handle the hierarchical structure of the data, that is dose levels nested within studies.

2.3 Dose–response meta-analysis

The aim of a dose–response meta-analysis is to reconstruct the shape of the association from multiple aggregated dose–response data. As compared to the previous strategies, it has the advantages of using the whole information available and being more informative. By describing the variation of the outcome over the entire exposure range, a dose–response meta-analysis allows to answer the following questions

- Is there any association between increasing dose levels and the outcome? If that's the case, what is the shape of the relationship?
- Which exposure values are associated with the minimum or maximum outcome value?
- Is there any difference in the study-specific dose–response associations? Which factors can explain the observed heterogeneity?

The methodology for dose–response meta-analysis was first presented by Greenland and Longnecker in their seminal paper (Greenland and Longnecker, 1992), which quickly became a standard reference for applied works. Indeed, the number of published dose–response meta-analyses increased exponentially from 9 in 2000 to 172 in 2016 (figure 2.2). The most popular fields of application include oncology, environmental and public health, nutrition epidemiology, and general internal medicine. Dose–response meta-analyses are published in many leading medical and epidemiological journals, including JAMA, Lancet, Stroke, Gastroenterology, American J of Medicine, American J of Clinical Nutrition, American J Epidemiology, International J Epidemiology, Journal National Cancer Institute, International J of Cancer, Statistics in Medicine

and many others. The method is also used by the World Cancer Research Fund/American Institute for Cancer Research for reviewing the evidence on the relations between life-style factors (e.g. diet and physical activity) and cancer. Guidelines based on these quantitative reviews are central to promote the overall health and prevent many chronic diseases.

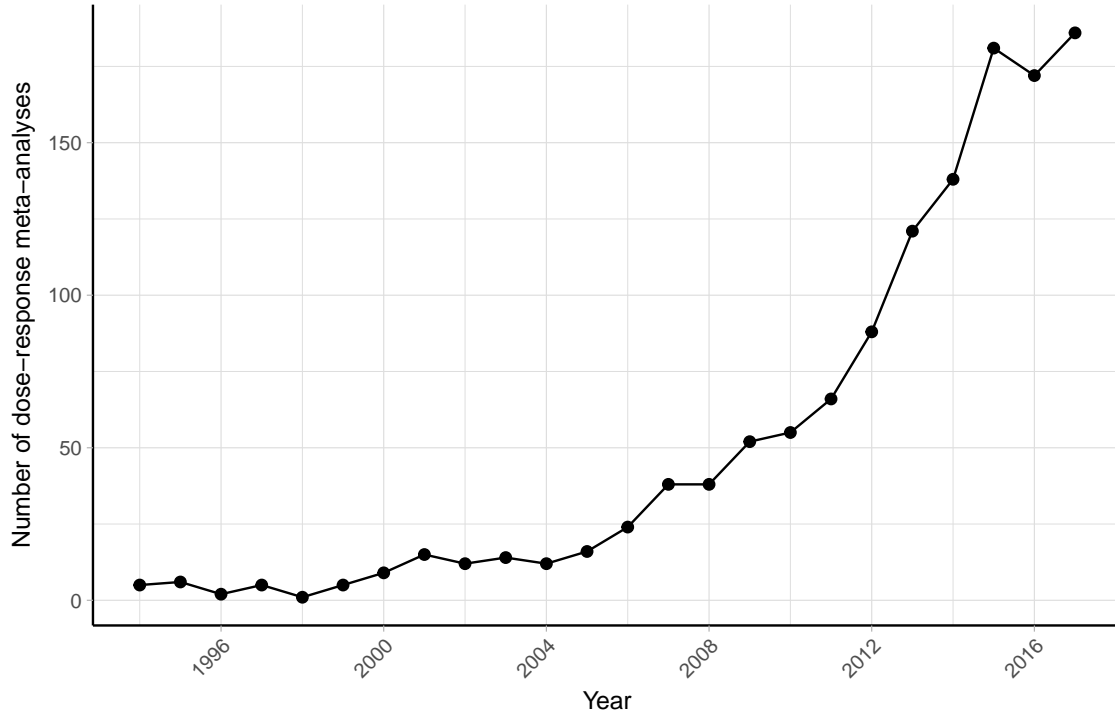


Figure 2.2: Number of citations of the paper by Greenland and Longnecker (1992) obtained from Google Scholar 1992-2017 (until December 2017).

The common approach for dose-response meta-analysis consists of a two-stage procedure, where the regression coefficients for the study-specific trends are first estimated separately within each study, and then combined using meta-analysis. In the next sections we cover the main methodological aspects related to each stage of the analysis.

2.3.1 First stage: study-specific trends

If we had access to the individual patient data, the dose-response model for a simple linear trend could be written as

$$\log(\lambda(x, \mathbf{z})) = \beta_0 + \beta_1 x + \boldsymbol{\gamma}^\top \mathbf{z} \quad (2.9)$$

with x the quantitative exposure and \mathbf{z} the set of possible confounders. The outcome variable is the log of a transformation of the mean outcome (e.g. odds, risk, or rate). Transformations of the exposure variable can be included to relax the linearity assumption, such as a quadratic term

$$\log(\lambda(x, \mathbf{z})) = \beta_0 + \beta_1 x + \beta_2 x^2 + \boldsymbol{\gamma}^\top \mathbf{z} \quad (2.10)$$

However, we have rarely access to the individual patient data and our inference is limited to a summary of the initial data. In particular, aggregated data from a categorical analysis can be often retrieved from published articles. The aim of the first stage of a dose–response meta-analysis is to estimate the β coefficients in equation 2.9 and 2.10 using aggregated dose–response data. We consider the notation presented in table 2.1 with $i = 1, \dots, I$ indexing the studies and $j = 1, \dots, J_i$ the non-referent dose levels of a generic i -th study. The corresponding two models can be written as

$$\log(\widehat{\text{RR}}_{ij}) = \log(\hat{\lambda}(x = x_{ij})) - \log(\hat{\lambda}(x = x_{i0})) = \beta_1(x_{ij} - x_{i0}) \quad (2.11)$$

$$\log(\widehat{\text{RR}}_{ij}) = \log(\hat{\lambda}(x = x_{ij})) - \log(\hat{\lambda}(x = x_{i0})) = \beta_1(x_{ij} - x_{i0}) + \beta_2(x_{ij}^2 - x_{i0}^2) \quad (2.12)$$

More generally, the i -th dose–response model is defined as

$$\mathbf{y}_i = \mathbf{X}_i \boldsymbol{\beta}_i + \boldsymbol{\varepsilon}_i \quad (2.13)$$

The outcome \mathbf{y}_i is the J_i length vector of the non-referent $\log \widehat{\text{RR}}$ s while \mathbf{X}_i the $J_i \times p$ design matrix containing the p transformations of the assigned dose used to model the dose–response association

$$\mathbf{X}_i = \begin{bmatrix} g_1(x_{i1}) - g_1(x_{i0}) & \dots & g_p(x_{i1}) - g_p(x_{i0}) \\ \vdots & & \vdots \\ g_1(x_{iJ_i}) - g_1(x_{i0}) & \dots & g_p(x_{iJ_i}) - g_p(x_{i0}) \end{bmatrix} \quad (2.14)$$

In the linear trend analysis (model 2.11), \mathbf{X}_i includes only the dose levels, $p = 1$, $g_1(x) = x$ (identity function)

$$\mathbf{X}_i = \begin{bmatrix} x_{i1} - x_{i0} \\ \vdots \\ x_{iJ_i} - x_{i0} \end{bmatrix}$$

while $p = 2$ columns are needed in the quadratic model 2.12: $g_1(x) = x$ and $g_2(x) = x^2$

$$\mathbf{X}_i = \begin{bmatrix} x_{i1} - x_{i0} & x_{i1}^2 - x_{i0}^2 \\ \vdots & \vdots \\ x_{iJ_i} - x_{i0} & x_{iJ_i}^2 - x_{i0}^2 \end{bmatrix}$$

A feature of the models 2.13 is the absence of the intercept term. The reference line in table 2.1 is not actually used for the estimation of the regression coefficients but introduces the constrain on the predicted $\log \widehat{\text{RR}}$, which needs to be 0 ($\widehat{\text{RR}} = 1$) for the reference dose value x_{i0} , as explicit in models 2.11 and 2.12.

Approximation of the covariance between $\log \widehat{\text{RR}}$

A particular characteristic of summarized dose–response data is that the $\log \widehat{\text{RR}}$ s are reported with different precision and are constructed using the same baseline group. Thus, the error

terms ϵ_i in equation 2.13 are heterogeneous and correlated, with a covariance matrix structured as

$$\text{Cov}(\epsilon_i) = \mathbf{S}_i = \begin{bmatrix} \sigma_{i11} & & & & \\ \vdots & \ddots & & & \\ \sigma_{i1j} & & \sigma_{ijj} & & \\ \vdots & & & \ddots & \\ \sigma_{i1J_i} & \dots & \sigma_{iJ_i j} & \dots & \sigma_{iJ_i J_i} \end{bmatrix} \quad (2.15)$$

with the variance of the log $\widehat{\text{RR}}$ s on the diagonal (σ_{ijj}) and the pairwise covariances as non-diagonal elements ($\sigma_{ijj'}$).

Two methods have been proposed to approximate the covariances $\sigma_{ijj'}$ (Greenland and Longnecker, 1992; Hamling *et al.*, 2008). Greenland and Longnecker described an algorithm to construct a table of pseudo or effective counts (number of cases and participants or person-time) that would produce the adjusted log $\widehat{\text{RR}}$ s as those published. A unique solution for the algorithm is ensured by keeping the margins of the pseudo-counts equal to the observed ones. Alternatively, Hamling *et al.* modified the previous algorithm in such a way that the pseudo-counts would also match the standard errors of the log $\widehat{\text{RR}}$ s.

Estimation

The dose-response coefficients β_i can be efficiently estimated using generalized least squares estimator (GLS), which minimizes the quadratic loss function $(\mathbf{y}_i - \mathbf{X}_i \beta_i)^\top \mathbf{S}_i^{-1} (\mathbf{y}_i - \mathbf{X}_i \beta_i)$ with respect to β_i assuming the covariance matrix \mathbf{S}_i known.

$$\begin{aligned} \hat{\beta}_i &= (\mathbf{X}_i^\top \mathbf{S}_i^{-1} \mathbf{X}_i)^{-1} \mathbf{X}_i^\top \mathbf{S}_i^{-1} \mathbf{y}_i \\ \widehat{\text{Var}}(\hat{\beta}_i) &= (\mathbf{X}_i^\top \mathbf{S}_i^{-1} \mathbf{X}_i)^{-1} \end{aligned} \quad (2.16)$$

The GLS estimates in equation 2.16 do not require any distributional assumption for the error terms. However, for the central limit theory, the error terms follow approximately a normal distribution $\epsilon_i \sim \mathcal{N}(\mathbf{0}, \mathbf{S}_i)$. Using this additional assumption, the log-likelihood of model 2.13 is

$$\ell(\beta_i) = -\frac{J_i}{2} \log(2\pi) - \frac{1}{2} |\mathbf{S}_i| - \frac{1}{2} [(\mathbf{y}_i - \mathbf{X}_i \beta_i)^\top (\mathbf{S}_i)^{-1} (\mathbf{y}_i - \mathbf{X}_i \beta_i)] \quad (2.17)$$

Interestingly, the maximum likelihood estimates that maximize the log-likelihood 2.17 coincides with the GLS estimates in 2.16 (Orsini *et al.*, 2006). Introducing the normality distribution for the random errors facilitates the inference, i.e. test of hypothesis and confidence intervals, on the β_i coefficients. The estimates in 2.16 are a linear combination of normal distributions ($\mathbf{y}_i \sim \mathcal{N}(\mathbf{X}_i \beta_i, \mathbf{S}_i)$) and therefore are also normally distributed $\hat{\beta}_i \sim \mathcal{N}(\beta_i, \text{Var}(\hat{\beta}_i))$.

The ML and GLS estimators always give unbiased estimates of β_i regardless of the specification of \mathbf{S}_i (Orsini *et al.*, 2006). As a consequence, also a weighted least square estimator (WLS) that assumes independence of the log $\widehat{\text{RR}}$ s will produce unbiased estimates. However, taking into account the correlation will improve the statistical properties of the estimator, in particular the efficiency. We investigated the differences between the GLS and WLS estimators using a

simulation study of 5000 aggregated dose–response data where the true trends were linear ($\beta_{\text{TRUE}} = -0.014$). As expected, both the estimators were unbiased and consistent but the empirical distribution of the GLS estimator was more concentrated around the true β value 2.3. The WLS estimates of the standard errors of the $\hat{\beta}_i$ were lower than the corresponding GLS values. This had a direct effect on the inference for the estimated linear trend. For instance, it may be interesting to fit a quadratic curve as in 2.12 and test the hypothesis $H_0 : \beta_2 = 0$, i.e. departure from a linear trend. Using inference based on WLS estimators the null hypothesis were wrongly rejected 3.96% of the time, lower than the nominal level $\alpha = 5\%$. The corresponding number for the GLS estimator was instead closer (4.8%). We also implemented simulations assuming a quadratic curve with the true coefficients $\beta_{\text{TRUE}} = (-0.092, 0.003)$. Similar results for the empirical bivariate distribution of $\hat{\beta}_i$ and their standard errors are presented in figure 2.4.

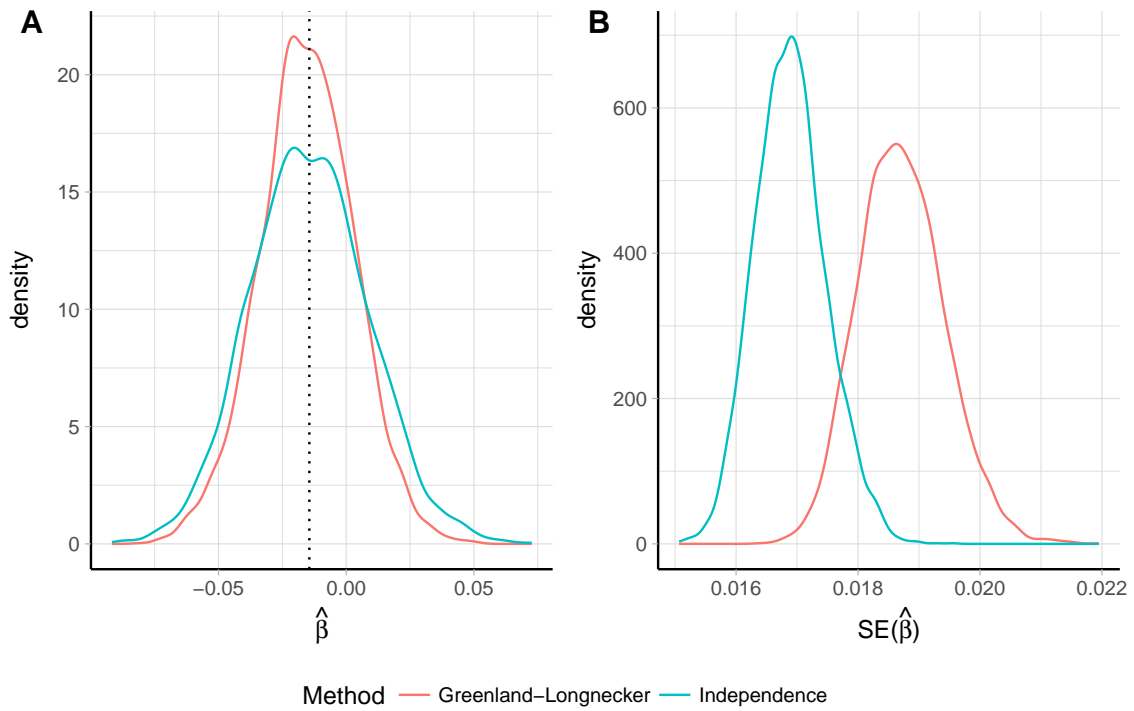


Figure 2.3: Empirical distribution of the $\hat{\beta}$ (panel A) and $\widehat{\text{Var}}(\hat{\beta}_i)$ (panel B) for a linear trend assuming independence of the log $\widehat{\text{RR}}$ and reconstructing the covariances using the Greenland and Longnecker’s method. Results are based on simulations with 5000 replications and a true linear trend $\beta = -0.014$.

2.3.2 Second stage: multivariate meta-analysis

The study-specific dose–response curves are defined by the p transformations, $g_1(x), \dots, g_p(x)$, and the estimated regression coefficients $\hat{\beta}_i$. A pooled dose–response can be obtained by combining the $\hat{\beta}_i$ coefficients. For that purpose, the same functional relationship needs to be defined across the studies. Therefore, the transformations of the exposure were not subscripted by the study index i .

The p length vector of the $\hat{\beta}_i$ parameters and the accompanying $p \times p$ covariances matrices

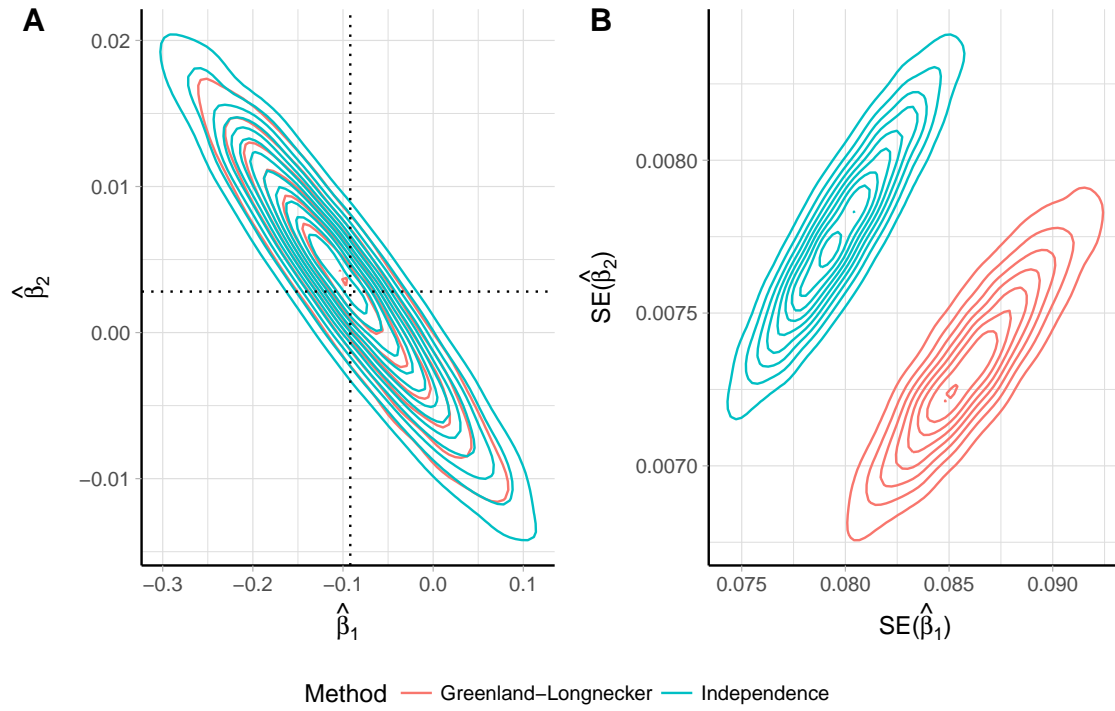


Figure 2.4: Empirical bivariate distribution of the beta coefficients (panel A) and their standard errors (panel B) for a quadratic trend assuming independence of the log \widehat{RR} and reconstructing the covariances using the Greenland and Longnecker's method. Results are based on simulations with 5000 replications and a true quadratic trend $\beta_1 = -0.092$, $\beta_2 = 0.003$.

$\widehat{\text{Var}}(\hat{\beta}_i)$ serve as outcome in the meta-analytic model. We consider the setting with $p \geq 2$ and relate the univariate case as a simpler instance of the more general multivariate case. Since the dimension of the outcome is no longer univariate, extensions of models 2.1 to the multivariate settings can be implemented for accommodating the synthesis of correlated estimates (Berkey *et al.*, 1998; Gasparrini *et al.*, 2012; Ritz *et al.*, 2008).

Model definition

A multivariate random-effects model has a similar formulation as in the univariate case

$$\hat{\beta}_i = \beta + \mathbf{b}_i + \varepsilon_i \quad (2.18)$$

The unobserved random effects \mathbf{b}_i are now of dimension p , still representing study-specific deviation from the mean β parameter. As before, they have zero mean $E[\mathbf{b}_i] = \mathbf{0}$ and $\text{Var}[\mathbf{b}_i] = \Psi$, the $p \times p$ between-study variance matrix. Specification of a parametric distribution for the random-effects may facilitate the inference (especially confidence intervals) and improve the prediction of marginal and conditional dose-response associations. Typically a multivariate normal distribution is adopted $\mathbf{b}_i \sim \mathcal{N}(\mathbf{0}, \Psi)$. Hence, we can write the marginal model of 2.18 as

$$\hat{\beta}_i \sim \mathcal{N}(\beta, \Sigma_i) \quad (2.19)$$

where the marginal variance $\Sigma_i = \widehat{\text{Var}}(\hat{\beta}_i) + \Psi$ is defined by the sum of the within-study and between-studies variance components. The model 2.19 implies a two-stage sampling procedure where the study-specific β_i parameters are assumed to be sampled from a multivariate normal distribution centered around the population average parameter β . The study-specific estimates $\hat{\beta}_i$ are themselves sampled from a multivariate distribution with zero mean and error variance assumed known.

The multivariate random-effects model 2.19 can be extended to meta-regression models by including study-levels covariates that might change the shape of the dose–response relationship. The dose–response coefficients are then modeled as a linear combination of the m study-level covariates $\mathbf{u}_i = (u_{i1}, \dots, u_{im})$, with $u_{i1} = 1$ indicating the intercept term

$$\hat{\beta}_i \sim \mathcal{N}(\tilde{\mathbf{X}}_i \beta, \Sigma_i) \quad (2.20)$$

The $p \times pm$ design matrix $\tilde{\mathbf{X}}_i$ is constructed taking the Kronecker product between the \mathbf{u}_i and the identity matrix of dimension p ($\mathbf{I}_{(p)}$)

$$\tilde{\mathbf{X}}_i = \mathbf{I}_{(p)} \otimes \mathbf{u}_i^\top = \begin{bmatrix} 1 & u_{i2} & \cdots & u_{im} & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & & & & \ddots & & & & \\ 0 & 0 & \cdots & 0 & \cdots & 1 & u_{i2} & \cdots & u_{im} \end{bmatrix} \quad (2.21)$$

For example, the $\tilde{\mathbf{X}}_i$ matrix relating the effect of a binary variable u_i to the dose–response coefficients for a quadratic trend is

$$\tilde{\mathbf{X}}_i = \mathbf{I}_{(2)} \otimes \mathbf{u}_i^\top = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \otimes (1, z_i) = \begin{bmatrix} 1 & u_i & 0 & 0 \\ 0 & 0 & 1 & u_i \end{bmatrix}$$

The dimension of $\hat{\beta}$ is now $m \times p$. The coefficients related to the intercept terms are interpreted as the mean dose–response coefficient when all the study-level covariates \mathbf{u} are equal to zero. The remaining coefficients indicate how the mean dose–response association vary with respect to the corresponding study-level covariate.

Estimation

Several methods are available for estimating the parameters of interest, namely the $p \times m$ dose–response coefficients in β and the $p(p+1)/2$ length vector ξ containing the elements of the between-studies covariance Ψ . There is generally no reason to assume a specific covariance structure (White *et al.*, 2011). We consider here likelihood-based estimators (Verbeke, 1997; Pinheiro and Bates, 2010). In particular, ML estimators estimate simultaneously β and ξ by maximizing the log-likelihood of the marginal model 2.20

$$\ell(\beta, \xi) = -\frac{1}{2} I p \log(\pi) - \frac{1}{2} \sum_{i=1}^I \log |\Sigma_i| - \frac{1}{2} \sum_{i=1}^I \left[(\hat{\beta}_i - \tilde{\mathbf{X}}_i \beta)^\top \Sigma_i^{-1} (\hat{\beta}_i - \tilde{\mathbf{X}}_i \beta) \right] \quad (2.22)$$

ML estimators, however, don't take into account the loss of degrees of freedom due to the β estimation Harville (1977). Alternatively, restricted maximum likelihood methods (REML) maximizes a set of contrasts defined as a function of the only covariance parameters

$$\ell_R(\xi) = -\frac{1}{2}(Ip - pm) - \frac{1}{2} \sum_{i=1}^I \log |\Sigma_i| - \frac{1}{2} \sum_{i=1}^I \log |\tilde{\mathbf{X}}_i^\top \Sigma_i \tilde{\mathbf{X}}_i| + \quad (2.23)$$

$$-\frac{1}{2} \sum_{i=1}^I \left[(\hat{\beta}_i - \tilde{\mathbf{X}}_i \beta)^\top \Sigma_i^{-1} (\hat{\beta}_i - \tilde{\mathbf{X}}_i \beta) \right] \quad (2.24)$$

Both estimation methods require iterative algorithms, where conditional estimates of $\hat{\beta}$ are plugged in either 2.22 or 2.24, regarded as function of ξ only, until convergence. More details on the implementation of iterative methods for maximizing equations 2.22 and 2.24 are described by Gasparrini *et al.* (2012).

Hypothesis testing and heterogeneity

There are two main domains of interest for making inference that relate either to the fixed-effects β or the variance components in Ψ . Using the normality assumption for the random-effects, inference is based on the approximated normal distribution for $\hat{\beta}$, with mean and covariance matrix defined similarly as in equation 2.16.

Since the mean dose-response association is defined by the β , the hypothesis of no association can be evaluated by testing $H_0 : \beta = \mathbf{0}$. Alternatively, a subset or linear combinations of β may be of interest. For example, in a quadratic trend the non-linearity is introduced by the quadratic term x^2 . Thus, testing $H_0 : \beta_2 = 0$ is a possible way for evaluating departure from a linear dose-response relationship.

As previously presented in section 2.1.2, the coefficients defining Ψ are not nuisance parameters rather than useful for quantifying the variation of the study-specific associations β_i . Similar measures for testing and quantifying the impact of heterogeneity have been extended to the multivariate setting (Berkey *et al.*, 1996). In particular, the Q statistic

$$Q = \sum_{i=1}^I (\hat{\beta}_i - \tilde{\mathbf{X}}_i \hat{\beta}_{fe})^\top \widehat{\text{Var}}(\hat{\beta}_i)^{-1} (\hat{\beta}_i - \tilde{\mathbf{X}}_i \hat{\beta}_{fe}) \quad (2.25)$$

with $\hat{\beta}_{fe}$ estimated under a fixed-effect model, is used to test $H_0 : \Psi = \mathbf{0}$. Under the null hypothesis, the Q statistic follow a χ^2 with $Ip - pm$ degrees of freedom. When $p = 1$ the formulations 2.4 and 2.25 coincide. The multivariate extension of the I^2 was derived relating the Q statistics to its degrees of freedom $I^2 = \max \left\{ 0, \frac{Q - (Ip - pm)}{Ip - pm} \right\}$ (Jackson *et al.*, 2012).

Prediction

Oftentimes the estimated mean coefficients $\hat{\beta}$ are not directly interpretable (an exception is the estimate for a linear trend). The dose-response results are thus communicated as predicted

(log) relative risk for selected exposure levels using one value as referent. Obtaining predictions either in a graphical or tabular presentation is thus an important step of the analysis and yet often poorly implemented. Based on the model 2.18, the predicted $\log RR$ for a dose level x_v using x_{ref} as referent can be calculated as

$$\log \widehat{RR}(x = x_v) = \mathbf{X}_v \hat{\boldsymbol{\beta}} \quad (2.26)$$

$$\text{Var}(\log \widehat{RR}(x = x_v)) = \mathbf{X}_v \widehat{\text{Var}}(\hat{\boldsymbol{\beta}}) \mathbf{X}_v^\top \quad (2.27)$$

where \mathbf{X}_v is the design matrix defined in the first-stage analysis (equation 2.14). For example, the predicted $\log RR$ for the quadratic model 2.12 comparing x_v versus x_{ref} is

$$\log \widehat{RR}(x = x_v) = \hat{\beta}_1 (x_v - x_{\text{ref}}) + \hat{\beta}_2 (x_v^2 - x_{\text{ref}}^2)$$

Of note, the referent dose x_{ref} is an arbitrary value and thus does not need to correspond to any of the study-specific reference values x_{i0} .

A confidence interval for the predicted $\log \widehat{RR}(x = x_v)$ is based on the normal distribution of $\hat{\boldsymbol{\beta}}$

$$\log \widehat{RR}(x = x_v) \mp z_{1-\alpha/2} \text{Var}(\log \widehat{RR}(x = x_v))^{\frac{1}{2}}$$

Formulas 2.26 and 2.27 can be extended to meta-regression models. The predicted $\log RR$ conditional on a specific study-level covariate pattern $\mathbf{z} = \mathbf{z}_v$ is

$$\log \widehat{RR}(x = x_v, \mathbf{z} = \mathbf{z}_v) = \mathbf{X}_v (\mathbf{I}_{(p)} \otimes \mathbf{Z}_v^\top) \hat{\boldsymbol{\beta}} \quad (2.28)$$

$$\text{Var}(\log \widehat{RR}(x = x_v, \mathbf{z} = \mathbf{z}_v)) = (\mathbf{X}_v \mathbf{Z}_v) \widehat{\text{Var}}(\hat{\boldsymbol{\beta}}) (\mathbf{X}_v \mathbf{Z}_v)^\top \quad (2.29)$$

2.3.3 Methodological research

Dose–response meta-analysis has received attention not only in applied works but also in theoretical articles that covered different aspects of the methodology. Greenland and Longnecker originally presented the two-stage approach for efficiently estimating a linear trend in a fixed-effect analysis. An alternative model for estimating curvilinear model, referred to as “pool first”, was also presented. The technique consists of a one-stage approach where the aggregated data are considered altogether and a single model as in 2.13 is fitted. By first combining the data, more flexible curve such as polynomials or splines can be estimated. The study-specific dose–response analyses are limited by the minimum number of non-referent log RRs across the studies. For example, if the aggregated data for a study consists of only one non referent log RR, only a univariate model with $p = 1$ can be estimated. The authors refined the methodology by extending the two-stage approach to allow for heterogeneity limited to a linear trend analysis (Berlin *et al.*, 1993).

Flexible dose–response models

The primary interest of the methodological research was in presenting alternative strategies for estimating non-linear curves. Bagnardi *et al.* described the use of fractional polynomials and restricted cubic splines using aggregated dose–response data (Bagnardi *et al.*, 2004). Based on a practical example on the association between alcohol consumption and all-cause mortality, the authors showed how implementation of these flexible techniques may prevent misleading results from conventional polynomials (e.g. quadratic) curves. Fractional polynomials of order two (FP2) consist of a large family of curves defined in the general form of

$$\text{FP2}(x) = \beta_1 x^{p_1} + \beta_2 x^{p_2} \quad (2.30)$$

where p_1 and p_2 are chosen in the set of power coefficients $\{-2, -1, -0.5, 0, 0.5, 1, 2, 3\}$ (Royston and Altman, 1994). When $p = 0$, x^p becomes $\log(x)$, while if $p_1 = p_2$ the second transformation of x becomes $x^{p_2} \log(x)$. The advantage of FP2 models is that different shapes, including U- and J-shapes, can be estimated by only two coefficients chosen using different combinations for the power terms (p_1, p_2) . Typically, the best fitting fractional polynomial is chosen in such a way that the (p_1, p_2) corresponds to the model with the highest likelihood, or equivalently, lowest deviance.

A popular alternative for flexibly model the dose–response association is represented by the use of splines (De Boor *et al.*, 1978), largely presented by Orsini *et al.* (2011b) using data from the Pooling Project of Prospective Studies of Diet and Cancer. Splines functions consist of consecutive polynomials connected at specific points of the exposure range called knots. Choosing $\mathbf{k} = (k_1, \dots, k_K)$ knots and third order polynomials, the model, also known as cubic splines (CS), is defined as

$$\text{CS}(x) = \beta_1 x + \beta_2 x^2 + \beta_3 x^3 + \sum_{l=1}^{K-1} \beta_{l+3} (x - k_l)_+^3 \quad (2.31)$$

where the ‘+’ notation has been used ($u_+ = u$ if $u \geq 0$ and $u_+ = 0$ otherwise). To avoid strange behaviors at the extremes of the exposure range, the model 2.31 is constraint to be linear before and after the first and last knots, respectively. For example, using three knots a restricted cubic spline model (RCS) can be specified in terms of two coefficients

$$\text{RCS}(x) = \beta_1 x + \beta_2 \left[(x - k_1)_+^3 - \frac{k_3 - k_1}{k_3 - k_2} (x - k_2)_+^3 + \frac{k_2 - k_1}{k_3 - k_2} (x - k_3)_+^3 \right] \quad (2.32)$$

The second transformation is generally divided by $(k_3 - k_1)^2$ to improve the numerical behavior and to put the spline transformations on the same scale (Harrell Jr, 2015).

The previous strategies have been often presented for exposures where 0 was the natural reference categories (e.g. alcohol consumption). Liu *et al.* (2009) extended the methodology for handling non-zero reference categories, as in the case of Body Mass Index. In particular, they first described how to construct the design matrix in terms of contrasts, as clarified in

equation 2.14. Misspecification of the design matrix (i.e. $\log RR = \beta_1(x_1 - x_0) + \beta_2(x_1 - x_0)^2$ instead of $\log RR = \beta_1(x_1 - x_0) + \beta_2(x_1^2 - x_0^2)$) may increase the risk of generating artifacts and misleading conclusions. Note that for zero exposure categories the problem is generally not relevant since many functions return zero for $x = 0$ ($g(0) = 0$).

Multivariate meta-analysis

The major contribution for estimating non-linear curves in a random-effects analysis came with the extension of univariate meta-analytic models to the multivariate case. The formalization and implementation of multivariate meta-analysis enabled the extension of a two-stage dose-response meta-analysis to the more complex case of multiple parameters association (Gasparini *et al.*, 2012). The multivariate framework can accommodate the synthesis of correlated outcomes, or estimates, derived in the first stage dose-response analyses. The application of the strategies presented in 2.30 and 2.32 in a random-effects setting has been easily facilitated by the implementation of dedicated packages for multivariate meta-analysis (White *et al.*, 2011; Jackson *et al.*, 2011).

More generally, the methodological advancements for meta-analysis were diverse and numerous (see Sutton and Higgins (2008) for an overview). Important improvements that directly affected how results are presented related mainly to the quantification and assessment of heterogeneity, with the definition of the measures presented in section 2.1.2. In addition, many other articles enriched the set of tools for pooling study-specific effects, with a direct application to the second stage of a dose-response meta-analysis. Among the many, it is worth to mention the implementation of several estimation methods for the between-study variability (see Langan *et al.* (2017) for a comparison based on simulation studies); advancement in performing meta-regression (Van Houwelingen *et al.*, 2002); proposal of sequential approaches (Pogue and Yusuf, 1997) and statistical power (Sutton *et al.*, 2007); and introduction of Bayesian methods (Sutton and Abrams, 2001).

Covariance and sensitivity analysis

Orsini *et al.* (2006) refined the initial formulas presented by Greenland and Longnecker for approximating the study-specific covariance matrices depending on the study-design. Berrington and Cox (2003) described an alternative method that avoids the reconstruction of the covariance matrices. Instead, upper and lower bounds for the covariance matrix are used in a sensitivity analysis of the dose-response coefficients, adopting a range of plausible values for the covariances. While the alternative algorithm proposed by Hamling *et al.* (2008) was presented in section 2.3.1, Easton *et al.* (1991) proposed the implementation of the floating absolute risks where the parameters and their standard errors can be estimated without specifying a baseline group and thus can be regarded as independent. Using individual patient data from the Pooling Project of Prospective Studies of Diet and Cancer (<http://www.hsph.harvard.edu/poolingproject>), negligible differences in the reconstructed covariance matrices were found comparing the three approaches (Orsini *et al.*, 2011b). Of

note, none of the methods would be needed if the authors of the original articles provided the covariance matrix along with the estimated coefficients, as it is usually done in consortia projects.

Berlin *et al.* (1993) presented alternatives for assigning the dose levels within exposure categories and illustrated the use of meta-regression models for investigating the possible effect of study-level characteristics on the estimated linear trends. Shi and Copas (2004) further discussed the issue of dose assignment in grouped measures allowing for arbitrary dose levels. In addition, they investigated the effect of heterogeneity and publication bias by means of sensitivity analyses. A similar problem of dose assignment was addressed by using a likelihood approach limited to a linear trend analysis (Takahashi and Tango, 2010). This idea has been further extended to the case of restricted cubic splines (Takahashi *et al.*, 2013).

2.3.4 Research questions

There are still many open research questions that need to be addressed to improve the synthesis of aggregated dose–response data. It was useful to observe the current practice in applied works in order to identify the more relevant questions. We search the PubMed database for articles published between January 1, 2013 and April 1, 2013 using the research query (“meta-analysis” [Title] and “dose-response” [Title]) and, after excluding irrelevant articles, found 42 applied dose–response meta-analyses. The authors of the select articles conducted a linear trend analysis most of the times (25 times, 60%) while only 17 articles considered non-linear associations by means of restricted cubic splines (15) and fractional polynomials (12). The papers modelling non-linear curves reported a graphical presentation of the pooled dose–response association.

Interestingly, none of the retrieved articles evaluated the goodness-of-fit of the selected dose–response model. The assessment of how the estimated curve fits the aggregated data should be a natural and important step in a dose–response analysis. In Paper II we will address this important issue by presenting relevant measures and graphical tools to help the assessment of goodness-of-fit.

The majority of the screened papers (39, 93%) quantify the impact of heterogeneity by reporting results for the Q test and the value of I^2 . While the limitations of the Q test approach are widely known, little emphasis is placed on the assumptions underneath the definition of the established measures of heterogeneity, i.e. all the estimates being reported with the same precision, which is unlikely to be met in almost all the applications. A measure of the impact of heterogeneity that does not require such an assumption would be desirable. In Paper III we overcome this limitation by proposing an alternative measure of heterogeneity and comparing the performance of the new and available measures.

None of the surveyed meta-analyses discussed the sensitivity of the overall dose–response relationship to differences in study-specific exposure distribution. This analysis can be very relevant in case of studies reporting results for heterogeneous exposure range and can enhance estimation by limiting the impact of extrapolation. The point-wise average approach presented

by Saurebrei and Royston in the context of individual patient data may represent an interesting alternative to the averaging of regression coefficients. In Paper IV we will evaluate the advantages of this strategy based on aggregated dose–response data.

In all the meta-analyses assessing departure from of linearity, the authors excluded those studies reporting less than two non-referent RRs. Indeed, a two-stage dose–response meta-analysis requires that all the models in the dose–response analysis are identifiable. A one stage approach would avoid that requirement. Such an approach is conceptually easier to understand, and more elegant from a statistical point of view. In addition, it allows investigation of much more flexible dose–response curves, that are not possible within the context of a traditional two-stage analysis. Aim of Paper V is to describe implementation and advantages of a one-stage random-effects dose–response meta-analysis of aggregated data.

The updated **dosresmeta** package implements also functions to facilitate specific aspects of a dose–response meta-analysis. These includes the assessment of goodness-of-fit discussed in Paper II, tests for fixed- and random-effects coefficients, conditional and marginal predictions, and the use of fractional polynomials.

2.4 Software

Dissemination of new statistical methodologies is certainly facilitated by the development and implementation of statistical software components. Many theoretical papers have not been considered in applied works because of lack of user-friendly software.

In 2006 Orsini et al. described the `glst` command in Stata, the first publicly available procedure dedicated for dose–response meta-analysis. The command implements both the one- and two-stage approaches limited, in case of a random-effects analysis, to a linear trend. A two-stage random-effects meta-analysis of non-linear relationships can be performed with the aid of the `mvmeta` command for multivariate meta-analysis. Several worked examples and codes are available at <http://www.imm.ki.se/biostatistics/glst/>. Later on, Li and Spiegelman wrote the macro `%metadose`, a similar procedure for SAS users.

The majority of the applied meta-analyses retrieved in our survey were performed using the `glst` procedure in Stata (36, 87%), while 2 used the `metadose` macro in SAS, 2 functions in RevMan. No dedicated package was available in the free software programming language R. Therefore, in 2013, we released the first version of the **dosresmeta** package on CRAN (<https://CRAN.R-project.org/package=dosresmeta>), a package specifically designed for dose–response meta-analysis in R, with specific functions that greatly facilitates the application in practical works.

The **dosresmeta** package is now available in the updated version 2.0.1 and new features are being implemented in the version under development on GitHub (<https://github.com/alecricri/dosresmeta>). Currently, the **dosresmeta** package is downloaded and used worldwide, with a median number of 260 downloads/month (Figure 2.5). The countries where it has been downloaded most are Great Britain (4005), United States (3905), and China (1605) (Figure 2.6). Working examples, codes, and data are available at <http://alecricri.github.io/>

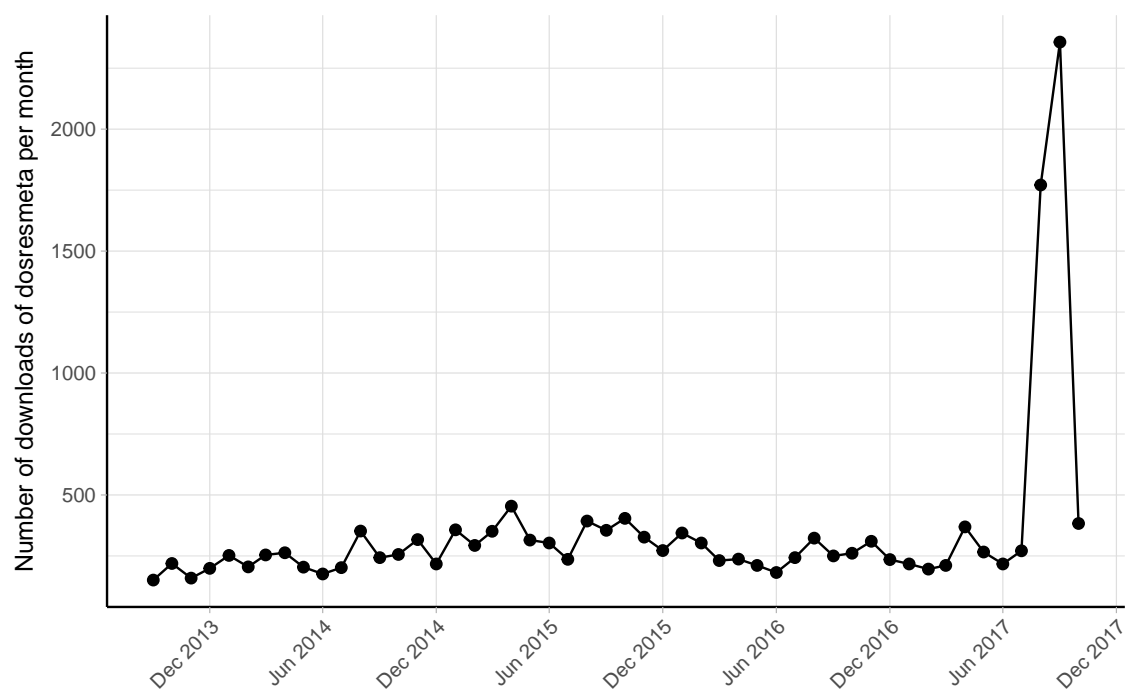


Figure 2.5: Monthly number of downloads of the dosresmeta R package from the RStudio CRAN mirror September 2013 - December 2017.

software for fully reproduce figures and numbers presented in both applied and theoretical papers.

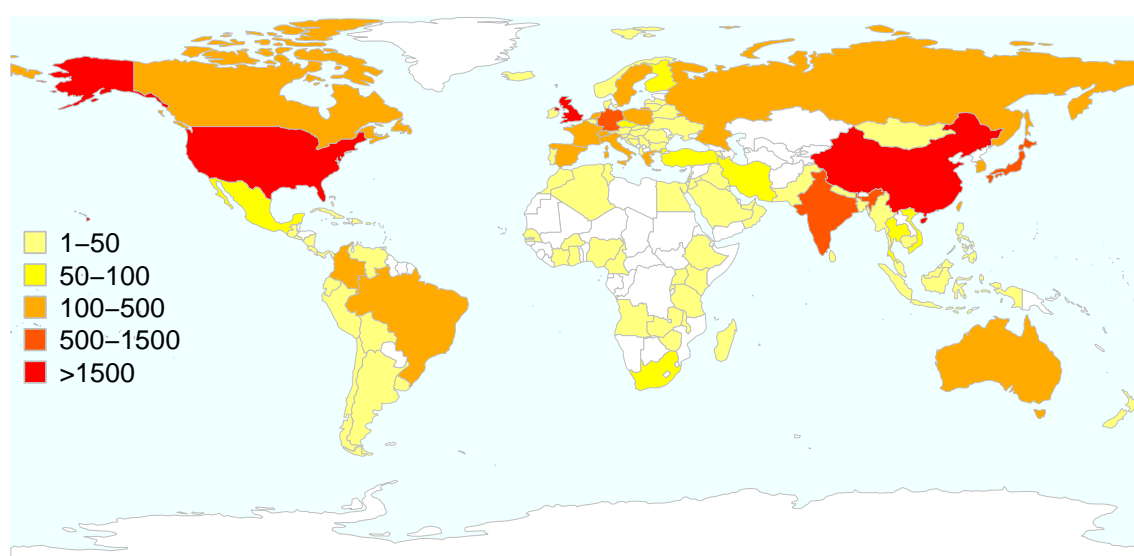


Figure 2.6: Total number of downloads of the `doseresmeta` R package worldwide from the RStudio CRAN mirror September 2013 - December 2017.

Chapter 3

Aims of the thesis

The overall aims of this thesis were to develop and implement new methods for dose–response in meta-analysis, in order to deal with the methodological aspects that have not yet been addressed.

More specifically, the aims were:

- To describe the implementation of the main aspects of a dose–response meta-analysis and the usage of the **dosresmeta** R package.
- To present and discuss relevant measures and graphical tools to assess the goodness-of-fit in dose–response meta-analysis.
- To develop a new measure of between-study heterogeneity in the broader context of meta-analysis and assess its properties as compared to other available measures.
- To explore possible advantages of a point-wise approach, especially, in case of dose–response meta-analysis where the exposure range varies substantially across the studies.
- To formalize and present an alternative one-stage random-effects model for dose–response meta-analysis of aggregated data, formulating the meta-analytic model in terms of a general linear mixed-effect model.

Chapter 4

Methods

4.1 The **dosresmeta** R package

The first version of the **dosresmeta** R package was released on the Comprehensive R Archive Network (CRAN) on September 9, 2013. It is listed in the CRAN task view Meta-Analysis (<https://CRAN.R-project.org/view=MetaAnalysis>), a guide that covers the vast collection of R packages for facilitating meta-analysis of summary statistics. New features and some minor bug fixes were implemented in further versions, including the major release (2.0.0 version) in August 17, 2017. The implementation of the package is presented in Paper I, which is also offered as a free guide for the package in a vignette accessible by typing `browseVignettes("dosresmeta")` from the R console.

4.1.1 Implementation

The initial version 1.0 of the **dosresmeta** R package implemented the two-stage approach for dose–response meta-analysis described in sections 2.3.1 and 2.3.2. The package included some facilities for efficiently estimating the dose–response associations across the included studies and used the **mvmeta** package for combining the study-specific regression coefficients (Gasparini *et al.*, 2012). The main novelty of the version 1.0 was the implementation of `gl` and `hamling` functions for reconstructing the covariance matrices among set of log relative risks using the methods developed by Greenland and Longnecker (1992) and Hamling *et al.* (2008). In version 1.3 dedicated functions were dedicated for summarizing and displaying results, and for predicting the pooled dose–response association as described in section 2.3.2. Compared to other routines, the `predict` function offers the possibility of deriving the predicted curve also for dose levels that are not observed in the analyzed data. The same applies for the choice of the reference dose value. The main advantage is that nice curves and tables including combined results for desired dose value can be easily obtained with a few lines of code. Practical examples are still available at <https://alecri.github.io/software/dosresmeta.html>. In addition, the `center` argument was added in the main function for centering the design matrix as described by Liu *et al.* (2009). The argument has been set to TRUE by default for preventing possible errors when modelling non-linear curves, especially in case of non-zero

exposure reference categories. Finally, additional arguments were introduced for allowing the specification of a list of covariance matrices directly by the user.

New capabilities and functions were written in the version under development available on GitHub and were finally included in the major release version 2.0 on CRAN. The **dosresmeta** package was largely redesigned in the internal functions but kept unchanged the external form and arguments for backward compatibility. Three main features were introduced: the extension of the two-stage approach for dose–response meta-analysis of differences in means (rather than log relative risks) (Crippa and Orsini, 2016a), the possibility of fitting meta-regression models and the implementation of an alternative one-stage approach. The first was achieved by extending the choices of the `covariance` argument for results presented in terms of mean and standardized mean differences, which related to the `covar.smd` function. The alternative `covariance == "indep"` can be specified for assuming independence of the log relative risks or differences in means. This is particularly useful when the information for reconstructing the covariances is not available (see additional (useful) code section on the referenced site for examples).

The implementation of the one-stage approach and related functions is discussed in more details in the methods for Paper V. The updated **dosresmeta** package implements also functions to facilitate specific aspects of a dose–response meta-analysis. These includes the assessment of goodness-of-fit discussed in Paper II, tests for fixed- and random-effects coefficients, conditional and marginal predictions, and the use of fractional polynomials.

Based on the last version of the **dosresmeta** package, an interactive interface is also available at <http://alessiocrippa.com/shiny/dosresmeta>. The web-app can be useful for introducing to the concepts of dose–response meta-analysis those researchers who are not familiar with the R software.

4.1.2 Description of the package

The **dosresmeta** package can be downloaded from CRAN by typing directly in R

```
R> install.packages("dosresmeta")
```

The version under development is instead available from GitHub

```
R> install.packages("devtools")
R> devtools::install_github("alecricri/dosresmeta")
```

The package consists of a main function `dosresmeta` with the following arguments

```
R> str(dosresmeta)
function (formula, id, v, type, cases, n, sd, data, mod = ~1, intercept = F,
  center = T, se, lb, ub, covariance = "gl", method = "reml", proc = "2stage",
  Slist, method.smd = "cohen", control = list())
```

The dose–response model is specified in the `formula` argument in a symbolic representation. For example, if `logrr` and `dose` are the variable name for the log relative risk and assigned

doses, a linear trend is specified as $\text{logrr} \sim \text{dose}$ while a quadratic curve as $\text{logrr} \sim \text{dose} + \text{I}(\text{dose})^2$. The variable are defined in a data.frame whose name is specified in the `data` argument. By default `intercept = FALSE` does not include the intercept term in the covariance matrix, which is constructed in terms of contrasted unless `center = FALSE`. The `id` argument specifies the name for the study id variable (can be omitted for single study analysis). The standard errors for the log relative risks is specified in the `se` argument, or alternatively, either the variances (`v`) or the lower (`lb`) and upper bounds (`ub`) of the relative risks need to be specified. The additional information about the study-design (`type`), the number of cases (`cases`), and participants or amount of person-time (`n`) is used for reconstructed the covariance of the log relative risk (or mean differences) using the method specified in the `covariance` argument (default is the Greenland and Longnecker's method). In alternatively, a list of covariance matrices can be passed to the `Slist` argument when `covariance = "user"`. As defaults, a two-stage procedure with REML estimation methods (`method`) are selected. Alternatives are a one-stage procedure (`proc = "stage"`) and either ML estimators `method = "ml"` or a fixed-effect analysis `method = "fixed"`. Residual heterogeneity can be modeled in a meta-regression analysis specified in the `mods` argument. For example, a different curve depending on the study design can be specified with `mods = ~ type`. Finally, a list of parameters can be passed to the `control` argument to control the fitting process.

The `dosresmeta` function returns an object of class “`dosresmeta`” with the information from the dose–response meta-analytic model. The `print` and `summary` methods display and produce a summary of the content of a `dosresmeta` object. The `predict` method facilitates the presentation of the results of a dose–response meta-analysis

```
R> str(dosresmeta:::predict.dosresmeta)
function (object, newdata, xref, expo = FALSE, xref_vec, ci.incl = TRUE,
  se.incl = FALSE, xref_pos = 1, delta, order = FALSE, ci.level = 0.95,
  ...)
```

where `object` contains the results of the `dosresmeta` function. A new data.frame with the desired doses can be passed to the `newdata` argument for obtaining the corresponding predicted log relative risks. If not provided, the predictions will be calculated for the assigned dose values across the studies. The `expo` argument can be set to `TRUE` to predict log relative risk and confidence intervals (unless `ci.incl = FALSE`) on the exponential scale. The referent value can be specified with the `xref` argument, or better, specifying the line of the `newdata` which serves as referent (`xref_pos` argument). For non-linear models the a vector need to be provided in `xref_vec` instead of `xref`. The `delta` argument is useful to predict the linear increase in the outcome for a delta increase in the exposure, and is thus only appropriate in a linear trend analysis. In the updated version of the **dosresmeta** package, a `blup` method has also been implemented to predict the study-specific random-effects and hence the conditional curves.

Additional functions can be listed

```
R> ls("package:dosresmeta")
[1] "covar.logrr"      "covar.smd"      "dosresmeta"
[4] "dosresmeta.control" "dosresmeta.fit" "fpgrid"
[7] "fracpol"          "gof"            "gr1"
[10] "hamling"          "vpc"            "waldtest"
```

Use `ls(getNamespace("dosresmeta"), all.names=TRUE)` for a complete list including hidden auxiliary functions.

4.2 Goodness-of-fit

The aim of Paper II was to address how to evaluate the goodness-of-fit in dose–response meta-analysis. The issue is particularly relevant in a dose–response analysis where the predicted curve should be a reasonably good summary of the modelled log relative risks. However, different features of aggregated dose–response data can complicate this comparison. The predicted curve is presented using a referent, x_{ref} , which may differ from the study-specific reference values. Thus the predicted and observed log relative risks can no longer be directly compared because their baseline group comparison is not the same. Even in the case where the reference values are all the same and equal to x_{ref} , the covariance among the study-specific RRs and the heterogeneity across the studies add further difficulties in evaluating if the chosen model provides a good summary of the observed data. Therefore, the proposed tools for assessing the goodness-of-fit are presented in a fixed-effect analysis where meta-regression models as in 2.20 are typically employed to explain the observed heterogeneity. We consider relevant measures, tests, and graphical tools that take into account the correlation of the observed data.

4.2.1 Deviance

The first natural measure of goodness-of-fit is a comparison between the predicted and observed data points, that is the non-referent log relative risks. This can be done by analyzing the residual term errors, which is defined by the difference between the observed log RRs y_i and the marginal prediction

$$\hat{e}_i = y_i - \mathbf{X}_i \mathbf{Z}_i \hat{\beta} \quad (4.1)$$

A summary for the error terms is the deviance

$$D = \sum_{i=1}^I (y_i - \mathbf{X}_i \mathbf{Z}_i \hat{\beta})^\top \mathbf{S}_i^{-1} (y_i - \mathbf{X}_i \mathbf{Z}_i \hat{\beta}) = \sum_{i=1}^I \hat{e}_i^\top \mathbf{S}_i^{-1} \hat{e}_i \quad (4.2)$$

The deviance D measures the total squared deviation between observed and predicted data taking into account the covariance matrices \mathbf{S}_i of the error terms. It is usually referred to as generalized residual sum of squares (GRSS) (Draper and Smith, 2014). Decreasing values of D indicate a better agreement between reported and fitted log RRs, with 0 being the lower bound that corresponds to perfect agreement (saturated model).

The D statistic can be used as a test for model specification. Under the null hypothesis that the model is correctly specified, D follows a χ^2 distribution with $df = n - pm$. This is equivalent to test if the residual variance, corrected for the correlation of the error terms, is larger than expected assuming that the dose-response model is correct. A small p value can be interpreted as evidence that the fitted model fails in accounting the observed variation in the log relative risks. As for the Q test, the deviance has no upper bound and is thus difficult to interpret the absolute value D .

4.2.2 Coefficient of determination

To complement the D statistic (and the corresponding test), the coefficient of determination, R^2 , can be used as a descriptive measure of goodness-of-fit (Hagquist and Stenbeck, 1998; Kvålseth, 1985). The R^2 is the complement to the unit of the ratio between the GRSS and the generalized sum of squares $GTSS = \sum_{i=1}^I \mathbf{y}_i^\top \mathbf{S}_i^{-1} \mathbf{y}_i$. Because the dose-response models do not have the intercept term, the R^2 can be defined as in Buse (1973); Theil (1958)

$$R^2 = 1 - \frac{GRSS}{GTSS} = 1 - \frac{\sum_{i=1}^I (\mathbf{y}_i - \mathbf{X}_i \mathbf{Z}_i \hat{\boldsymbol{\beta}})^\top \mathbf{S}_i^{-1} (\mathbf{y}_i - \mathbf{X}_i \mathbf{Z}_i \hat{\boldsymbol{\beta}})}{\sum_{i=1}^I \mathbf{y}_i^\top \mathbf{S}_i^{-1} \mathbf{y}_i} \quad (4.3)$$

The R^2 is a dimensionless number that is bounded between 0 and 1, and can be generally interpreted as the proportion of the generalized total sum of squares explained by the dose-response model and study-level covariates. The lower bound 0 corresponds to the case where all the β coefficients are equal to 0 and therefore the model is not able to explain the variability in the observed log relative risks. Contrary, the upper bound 1 indicates a perfect agreement between reported and fitted data.

By construction the R^2 can not decrease as the number of regression coefficients increases. A penalized, or adjusted, version that takes into account this behavior can be defined

$$R_{\text{adj}}^2 = 1 - \frac{n}{n - pm} (1 - R^2) \quad (4.4)$$

Possibly, a low R^2 may indicate that more flexible transformations of the exposure are needed, or that there is considerable residual variability that might be explained by study-level covariates.

4.2.3 Visual tools

The visual assessment of the goodness-of-fit may reveal specific patterns in the data that might otherwise go undetected by only looking at summary measures such as the deviance and the coefficient of variation (Kvålseth, 1985). The graphical comparison can sometimes be delicate because different factors may affect such analysis. The aggregated dose-response data are presented using one group as comparison. This feature has two important consequences when deducting an overall trend from the reported (log) relative risks. The former is that

different parameterizations, or models, can be graphically compared only if the predicted risk for the reference category is similar. The latter, instead, involves the correlation of the modelled data points which makes even harder to evaluate if a specific model fits the reported data. To illustrate both the problems we consider IPD from one of the registers involved in the Surveillance, Epidemiology, and End Results (SEER) Program (<https://seer.cancer.gov>), and focus on the association between age at diagnosis and breast cancer mortality.

Table 4.1: Aggregated dose-response data on the adjusted association between age and breast cancer mortality based on one registry from the SEER program using the first age category as referent.

Age category	Mean age	Cases	Person-years	IRR	95% CI	log IRR	SE
[20,35]	32.4	56	2099.3	1.00		0.00	0.00
(35,60]	49.7	451	37585.3	0.68	(0.51, 0.9)	-0.39	0.14
(60,70]	65.6	220	20590.7	0.71	(0.53, 0.96)	-0.34	0.15
(70,97]	77.0	215	17896.5	0.77	(0.57, 1.04)	-0.27	0.15

Using 35, 60, 70 year as cut points, we modelled age using 5 categories in a Poisson model adjusting for potential confounders and produced aggregated dose-response results in table 4.1, using the first category as referent. Using the methodology presented in section 2.3.1, we estimated a linear trend a graphically compared the predicted trend and the tabular data (figure 4.1). While the reported log RRs suggest an inverse association between age and breast cancer mortality, the estimated linear trend indicates opposite conclusion (a 0.17% increase in mortality for every 5-year increase of age at diagnosis). The linear trend does not seem to properly fit the data since the fitted lined doesn't event pass through the reported log RRs. The problem is that there are few cases in the reference age category and so the log RRs are more unstable. By changing the group comparison to the second age category, this issue is partially solved. To address the further issue of the covariance, we proposed graphical tools based on the analysis of the decorrelated residuals.

The residuals can be decorrelated using the Cholesky factorization of the covariance matrices $\mathbf{S}_i = \mathbf{C}_i \mathbf{C}_i^\top$, with \mathbf{C}_i being a lower triangular matrix $J_i \times J_i$. The decorrelated residuals $\hat{\mathbf{e}}_i^*$ are then calculated as

$$\hat{\mathbf{e}}_i^* = \mathbf{C}_i^{-1} (\mathbf{y}_i - \mathbf{X}_i \mathbf{Z}_i \hat{\boldsymbol{\beta}}) = \mathbf{C}_i^{-1} \hat{\mathbf{e}}_i \quad (4.5)$$

and plotted against the exposure. Such a graphical analysis is the equivalent of a residual vs. predictors/predicted outcome plot after a model estimated through ordinary least squares. Since the variables in the plot are transformed, the actual value of the decorrelated residuals is not directly interpretable. However, it is still possible to detect specific patterns for the residuals over the exposure range. In such a case, the plot can indicate lack of fit of the fitted model for select exposure values. Overlaying a locally weighted scatterplot smoothing (LOWESS) may help to visualize possible patterns, while a different shape or color for the residuals can distinguish them according to study-level covariates in case of meta-regression models.

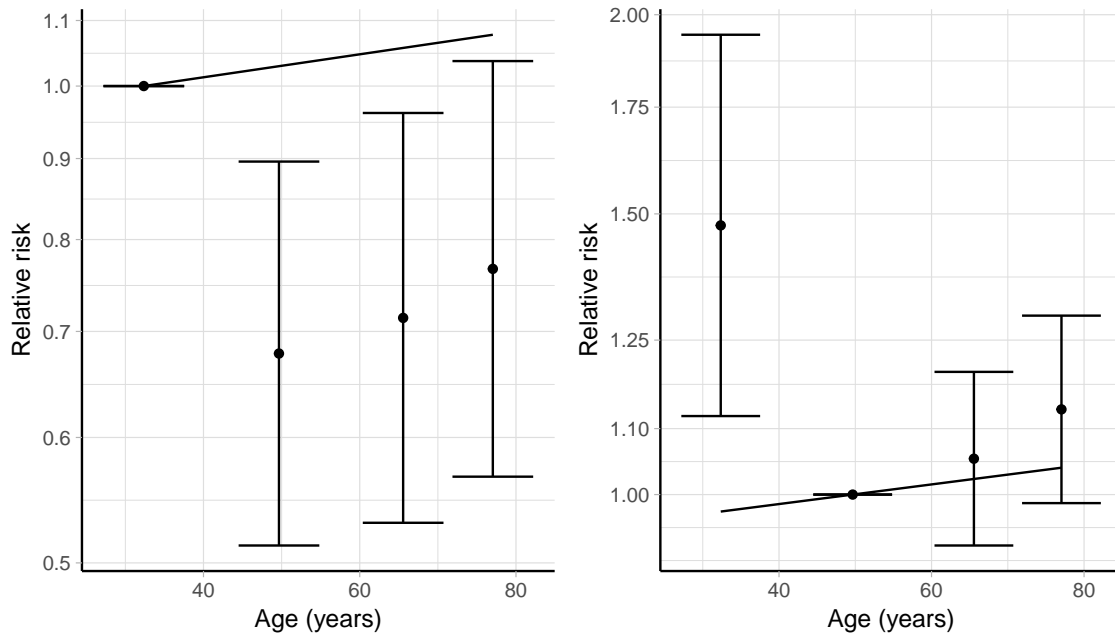


Figure 4.1: Comparison between observed and fitted data using changing the comparison group from the first age category (left panel) to the second one (right panel) based on the aggregated data on the association between age and breast cancer mortality presented in table 4.1

4.3 A new measure of heterogeneity

One of the possible reasons for large values of D or similarly small values of R^2 is presence of heterogeneity in the dose–response associations. The measures of heterogeneity presented in section 2.1.3, namely \hat{R}_I and I^2 were derived based on the assumption of homogeneity for the error variance terms v_i , which is unlikely to be met in applications. To illustrate this point, let us consider the two hypothetical distributions for the within-study error terms in table 4.2. The distribution of v_i in the first example (analysis A) is much more homogeneous compared to the second scenario (analysis B). The coefficient of variation for the v_i in the second example is 20 times higher than the corresponding number in the first scenario. While it seems reasonable to assume homogeneity of the v_i for the analysis A, in the second case this hypothesis is not appropriate. Nonetheless both \hat{R}_I and I^2 would summarize the two distributions with a single common number.

Table 4.2: Hypothetical distributions of within-study errors in two meta-analyses of 5 studies.

Analysis	v_1, \dots, v_5	CV_{v_i}	s_1^2	s_2^2
A	5, 5.2, 4.9, 5.3, 4.8	0.04	5.0	5.0
B	4, 17, 15, 2, 3.8	0.84	5.0	4.4

4.3.1 Definition and properties

The available measures relate the between-study heterogeneity to the overall variability, whose definition also varies across a study. A different prospective consists of measuring the impact of heterogeneity in determining the variance of the combined effect in a random-effects analysis. This quantity depends on the τ^2 and on the variance of the combined $\hat{\beta}$, quantities that don't require the assumption of homogeneity for the within-study error terms.

To determine how τ^2 contributes to give $\widehat{\text{Var}}(\hat{\beta})$, we consider the hypothetical case where all the estimates $\hat{\beta}_i$ are reported with no error, i.e. $v_i = 0 \forall i = 1, \dots, I$. The weights used in the meta-analytic model depends only on τ^2 , and following equation 2.3 the variance of the combined effect is $\widehat{\text{Var}}(\hat{\beta}) = \left(\sum_{i=1}^I \hat{\tau}^2\right)^{-1} = \hat{\tau}^2/I$. In the more realistic case where $v_i > 0$, the variance of $\hat{\beta}$ will increase to incorporate the uncertainty in the reported estimates. The contribution of the heterogeneity is still defined by $\hat{\tau}^2/I$. The new measure of heterogeneity, R_b , can be written as

$$\hat{R}_b = \frac{\hat{\tau}^2}{I\widehat{\text{Var}}(\hat{\beta})} = \frac{\hat{\tau}^2}{I/\left(\sum_{i=1}^I \frac{1}{v_i + \hat{\tau}^2}\right)} = \frac{1}{I} \sum_{i=1}^I \frac{\hat{\tau}^2}{\hat{\tau}^2 + v_i} \quad (4.6)$$

The \hat{R}_b is a dimensionless number that can be expressed as a percentage, ranging from 0% (corresponding to $\hat{\tau}^2 = 0$, i.e. no observed heterogeneity) to 100%, for the hypothetical case where all the effects are estimated with no error. The proposed measure is defined as a function of the estimated heterogeneity (τ^2), the number of studies (I), and the within-study error terms (v_i). It satisfies the criteria required for a measure of heterogeneity (Higgins and Thompson, 2002): it is a non-decreasing function of $\hat{\tau}^2$, it is invariant to scale transformation of the estimates, and is not intrinsically affected by the number of studies included in the analysis. Similarly to \hat{R}_I and I^2 , the proposed measure is a function on the within-error terms v_i and so it tends to 1 in case of meta-analysis of very precise estimates, even for relative small values of $\hat{\tau}^2$. As already mentioned in section 2.1.3, the use of the between-studies coefficient of variation can complement these measures (Takkouche *et al.*, 1999).

The right hand of equation 4.6 expresses \hat{R}_b as an average of the ratios of the $\hat{\tau}^2$ to the study-specific overall variance $v_i + \hat{\tau}^2$. It is easy to derive that \hat{R}_b coincides with the definition of \hat{R}_I and I^2 in case of homogeneity of the v_i . When the within-errors vary across study, the difference between \hat{R}_b and I^2 will depend on the actual values of v_i , while it can be proven that $\hat{R}_b \leq \hat{R}_I$.

An estimate of the between-study heterogeneity is required for the computation of \hat{R}_b as well for the alternative measures \hat{R}_I and I^2 . The moment-based estimator presented in equation 2.5 is a standard choice in many applied meta-analyses and has the advantage of having a closed formulation. In addition, the estimator is asymptotically consistent (Jackson *et al.*, 2010). Using this estimation method, \hat{R}_b can be expressed as a function of the Q statistic

$$\hat{R}_b = \frac{1}{I} \sum_{i=1}^I \frac{Q - (I - 1)}{Q + a_i - (I - 1)} \quad (4.7)$$

with $a_i = v_i \left(\sum_{i=1}^I w_i - \sum_{i=1}^I w_i^2 / \sum_{i=1}^I w_i \right)$. The asymptotic variance for \hat{R}_b can be derived by using the delta method on the relation 4.7

$$\widehat{\text{Var}}(\hat{R}_b) \approx \left(\frac{1}{I} \sum_{i=1}^I \frac{a_i}{(Q + a_i - (I - 1))^2} \right)^2 \text{Var}(Q) \quad (4.8)$$

The formula for $\text{Var}(Q) = 2(I - 1) + 4 \left(S_1 - \frac{S_2}{S_1} \right) \tau^2 + 2 \left(S_2 - 2 \frac{S_3}{S_1} + \frac{S_2^2}{S_1^2} \right)$, with $S_r = \sum_{i=1}^I w_i^r$, was first presented by Biggerstaff and Tweedie (1997).

When the number of studies is large, \hat{R}_b is asymptotically distributed and thus Wald-type confidence interval can be constructed $\hat{R}_b \pm z_{1-\alpha/2} \sqrt{\widehat{\text{Var}}(\hat{R}_b)}$.

4.4 A point-wise approach

Measures of heterogeneity are frequently employed in applied works and in applications of meta-regression models. In a dose–response meta-analysis, however, there are two aspects of heterogeneity that can not be captured using standard methods. More specifically, in a two-stage analysis the same functional transformations g_1, \dots, g_p need to be defined for all the studies so that the regression coefficients can be properly combined by meta-analysis. This may have important consequences in case the chosen dose–response model adequately fits only a subset of the analyzed studies. To illustrate this aspect, we consider a subset of 4 studies on the association between milk consumption (ml/day) and all-cause mortality (Larsson *et al.*, 2015). We modelled the individual curves using FP2 and selected in each study the combination of power terms which maximized the log likelihood (or equivalently with the minimum AIC). The chosen power terms in the individual analyses differ although the predicted curves describe a similar association figure 4.2. Forcing a unique set of power terms may decrease the fit of some of the study-specific analyses and thus produce more unstable estimates for the dose–response parameters.

An other difficulty may be encountered in uniformly defining the g transformation across the studies. For instance, we might decide to model the previous association between milk consumption and mortality using RCS. A percentile approach is commonly adopted for choosing where to place the k in equation 2.32. The first and third knots are located at the extremes, generally at the 10-th and 90-th percentiles of the exposure distribution, while the median exposure value is chosen for the remaining knot. If the exposure distributions largely vary (especially in terms of range definition), as it is in this case, it may not be possible to equally locate the knots in all the studies. Indeed, in our example only one study considered dose levels higher than the upper knot (433 ml/day). As a consequence, the second spline transformation for the other studies will be equal 0 and the model is not estimable (the design matrix is not invertible).

A second related problem directly affects the prediction of the pooled log relative risks. The maximum dose levels varies largely across studies, with values 715,441,369,146 ml/day. The predictions from the second stage analysis, however, are obtained using the combined $\hat{\beta}$, which

disregard information about the exposure ranges. All the studies contribute in predicting the log relative risks, even if some of them only reported results for low exposure values. In such a way, the combined curve may severely affected by these extrapolations.

A pointwise approach for meta-analysis of aggregated dose-response data may properly address the described issues.

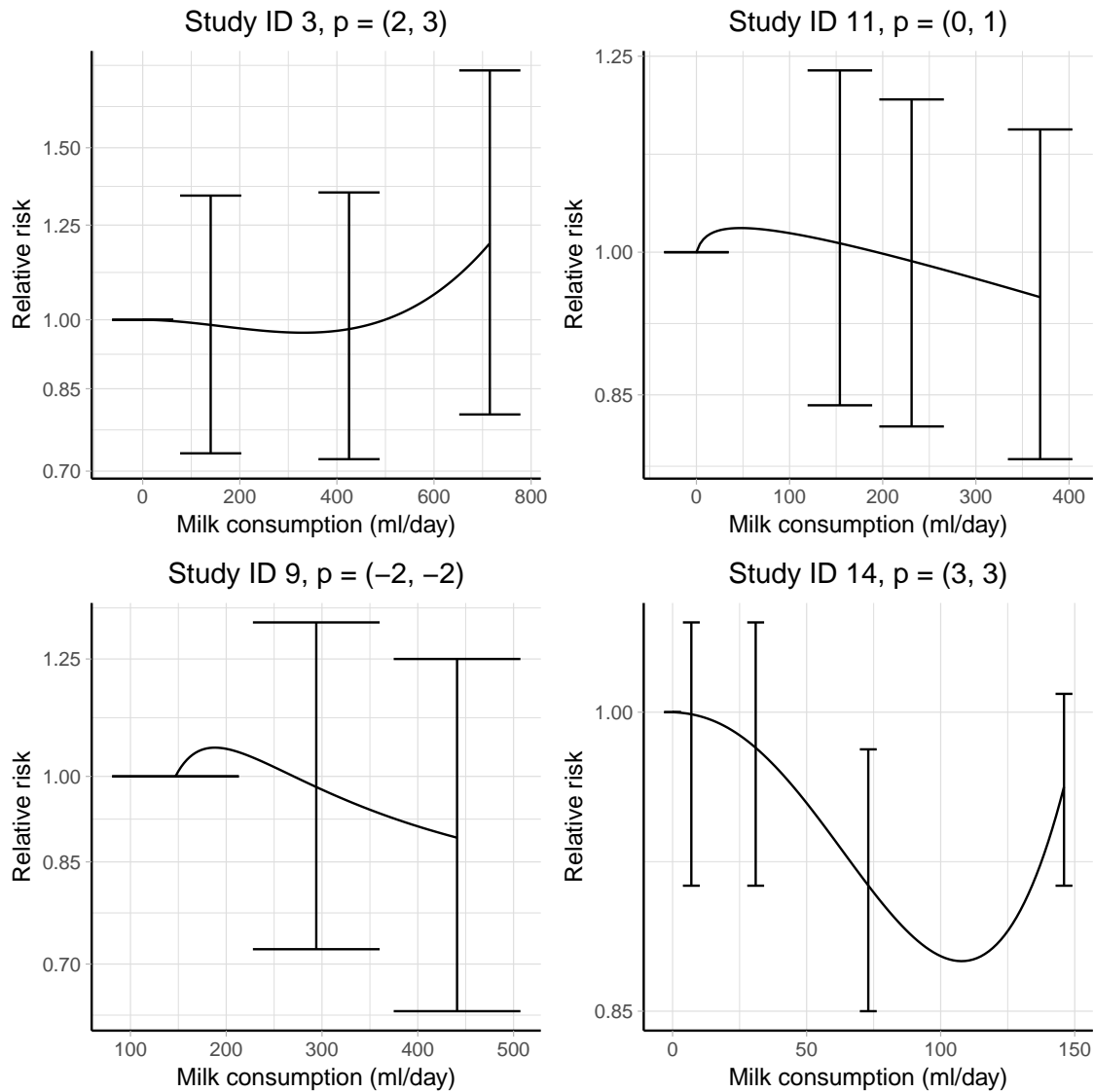


Figure 4.2: Dose-response associations between milk consumption (ml/day) and all-cause mortality in 4 studies. The curves are modelled using fractional polynomials with the sets of power terms p (reported in the title) chosen by maximizing the study-specific likelihoods. The results are presented on the log scale using the observed reference values as comparators.

A pointwise approach was first presented by Sauerbrei and Royston (2011) for meta-analysis of continuous covariates based on IPD. The strategy consists of separately estimating the study-specific curves and, based on them, calculating the predicted log relative risks for selected exposure values. The combined curve is obtained by pooling the predicted relative risks instead of calculating them from the combined regression coefficients. The described methodology

has the advantage of fitting potential diverse curves across the studies, and limiting the study-specific predicted log relative risks to the observed exposure range.

4.4.1 Estimation and prediction of study-specific curves

The first step of a pointwise approach is similar to the methodology presented in section 2.3.1 with the difference that the g transformations in the design matrices 2.14 are subscripted by the study index i , to highlight that they may differ across the studies, also in terms of number (p_i)

$$\mathbf{X}_i = \begin{bmatrix} g_{i1}(x_{i1}) - g_{i1}(x_{i0}) & \dots & g_{ip_i}(x_{ip_i}) - g_{ip_i}(x_{i0}) \\ \vdots & & \vdots \\ g_{i1}(x_{iJ_i}) - g_{i1}(x_{i0}) & \dots & g_{ip_i}(x_{iJ_i}) - g_{ip_i}(x_{i0}) \end{bmatrix} \quad (4.9)$$

For example, different power terms for FP2 can be chosen or, for a RCS analysis, the knots can be located separately in each study. Potentially, a mixed of curves could be also estimated across the study in order to improve the fit of the individual dose–response analyses. The regression coefficients are then be estimated using generalized least squares estimators presented in equation 2.16.

Once the curves have been estimated, the results of the first step analysis are presented in terms of predicted log relative risks of a set of v_i exposure values \mathbf{x}_{v_i} using a suitable value x_{ref} as comparator. The i indexed is used to highlight that the chosen dose values may differ across the studies. In particular, the predictions in each study can be limited to the observed exposure range $\max(\mathbf{x}_{v_i}) \leq \max \mathbf{x}_i$.

$$\hat{\mathbf{y}}_i = \mathbf{X}_{v_i} \hat{\boldsymbol{\beta}}_i \quad (4.10)$$

$$\hat{\mathbf{v}}_i = \text{diag}(\mathbf{X}_{v_i} \widehat{\text{Var}}(\hat{\boldsymbol{\beta}}_i) \mathbf{X}_{v_i}^\top) \quad (4.11)$$

with formulas similar to those presented in equation 2.26 and 2.27, with the notable difference that the predictions are based on the study-specific $\hat{\boldsymbol{\beta}}_i$ rather than the mean $\hat{\boldsymbol{\beta}}$ coefficients.

4.4.2 Averaging of dose–response prediction

In a pointwise strategy the combined dose–response curve is derived by pooling the study-specific predicted log relative risks derived in equation 4.10. The second step analysis consists of $v = \max(v_i)$ univariate meta-analyses where the effect sizes are the elements in $\hat{\mathbf{y}}_i$ with the within-error variances $\hat{\mathbf{v}}_i$. The combined predicted relative risks are estimated using the weighted average presented in equation 2.2.

As a final result, the combined dose–response curve is graphically presented as a smooth function of the combined predicted relative risks for the chosen v dose levels. In addition, all the results of the univariate meta-analyses can be pointwisely presented, such as estimates of the heterogeneity τ^2 and related measures, R_b , I^2 , and R_i , the Q statistic, and the study-specific weights, with the potential of a much richer set of results.

4.5 A one-stage model

The study-specific dose–response analysis in a standard two-stage or alternative pointwise approach suffer from the limited number of data points. Most of the individual studies present results for 2 to 4 non-referent exposure categories, but cases where dichotomization of the exposure occurred are not rare (Turner *et al.*, 2010). In the latter case, only dose–response models parameterized by $p = 1$ coefficient can be estimated (e.g. linear trend). Indeed, a standard requirement for meta-analysis of non-linear curves is that the studies provide at least two non-referent relative risks.

The extension of the one-stage approach to a random-effects meta-analysis may overcome the constrain from the limited number of individual data points. A one-stage approach is conceptually easier since the entire analysis can be formulated in a single statistical model. Flexible curves characterized by multiple parameters ($p > 3$) can be easily accommodated, so that more elaborate research questions can be answered, without losing the information from those studies usually excluded in a two-stage analysis.

4.5.1 Model definition

A one-stage dose–response meta-analysis can be written in the form of a linear mixed-effects model

$$\mathbf{y}_i = \mathbf{X}_i \boldsymbol{\beta} + \mathbf{Z}_i \mathbf{b}_i + \boldsymbol{\varepsilon}_i \quad (4.12)$$

where the terms \mathbf{y}_i , \mathbf{X}_i , and $\boldsymbol{\varepsilon}_i$ are defined exactly as those presented in the first step of a two-stage analysis (equation 2.13). The quantities $\boldsymbol{\beta}$ and \mathbf{b}_i , instead, are the population average parameter and unobserved random-effects as defined in second step (equation 2.18). The additional \mathbf{Z}_i is the $n_i \times p$ design matrix for the random-effects and coincides with the definition of \mathbf{X}_i .

Placing the multivariate distribution for the random-effects terms, the marginal model for a one stage analysis is

$$\mathbf{y}_i \sim \mathcal{N}(\mathbf{X}_i \boldsymbol{\beta}, \mathbf{Z}_i \boldsymbol{\Psi} \mathbf{Z}_i^\top + \mathbf{S}_i) \quad (4.13)$$

Similarly, the conditional model is defined as

$$\mathbf{y}_i | \mathbf{b}_i \sim \mathcal{N}(\mathbf{X}_i \boldsymbol{\beta} + \mathbf{Z}_i \mathbf{b}_i, \mathbf{S}_i) \quad (4.14)$$

Note that the conditional and marginal models are now defined for the log relative risks rather than the dose–response coefficients. In particular, the definition of the marginal variance $\boldsymbol{\Sigma}_i = \mathbf{Z}_i \boldsymbol{\Psi} \mathbf{Z}_i^\top + \mathbf{S}_i$ is quite different. It depends not only on the within and between components but also on the corresponding dose value x_{ij} (or equivalently z_{ij}) associated with y_{ij} .

Meta-regression models can be estimated by including in \mathbf{X}_i the interaction terms between the p transformations of the exposure variable and study-level covariates, while leaving unchanged the definition of the \mathbf{Z}_i matrix for the random-effects. Assuming a quadratic curve and a binary study-level covariate u_i , the design matrices for the fixed- and random-effects can

be written as

$$\mathbf{X}_i = \begin{bmatrix} x_{i1} - x_{i0} & x_{i1}^2 - x_{i0}^2 & (x_{i1} - x_{i0})u_i & (x_{i1}^2 - x_{i0}^2)u_i \\ \vdots & \vdots & \vdots & \vdots \\ x_{iJ_i} - x_{i0} & x_{iJ_i}^2 - x_{i0}^2 & (x_{iJ_i} - x_{i0})u_i & (x_{iJ_i}^2 - x_{i0}^2)u_i \end{bmatrix}$$

$$\mathbf{Z}_i = \begin{bmatrix} x_{i1} - x_{i0} & x_{i1}^2 - x_{i0}^2 \\ \vdots & \vdots \\ x_{iJ_i} - x_{i0} & x_{iJ_i}^2 - x_{i0}^2 \end{bmatrix}$$

4.5.2 Estimation and hypothesis testing

The parameters to be estimated are the $m \times p$ fixed effects and the $p \times (p + 1)/2$ elements of the between-study variance matrix. We consider likelihood-based estimators that maximize either the log-likelihood of model 4.14

$$\ell(\boldsymbol{\beta}, \boldsymbol{\xi}) = -\frac{1}{2}n \log(2\pi) - \frac{1}{2} \sum_{i=1}^k \log |\boldsymbol{\Sigma}_i(\boldsymbol{\xi})| - \frac{1}{2} \sum_{i=1}^k \left[(\mathbf{y}_i - \mathbf{X}_i \boldsymbol{\beta})^\top (\boldsymbol{\Sigma}_i(\boldsymbol{\xi}))^{-1} (\mathbf{y}_i - \mathbf{X}_i \boldsymbol{\beta}) \right] \quad (4.15)$$

or the corresponding restricted version

$$\begin{aligned} \ell_R(\boldsymbol{\xi}) = & -\frac{1}{2}(n-p) \log(2\pi) - \frac{1}{2} \sum_{i=1}^k \log |\boldsymbol{\Sigma}_i(\boldsymbol{\xi})| - \frac{1}{2} \log \left| \sum_{i=1}^k \mathbf{X}_i^\top (\boldsymbol{\Sigma}_i(\boldsymbol{\xi}))^{-1} \mathbf{X}_i \right| + \\ & - \frac{1}{2} \sum_{i=1}^k \left[(\mathbf{y}_i - \mathbf{X}_i \hat{\boldsymbol{\beta}})^\top (\boldsymbol{\Sigma}_i(\boldsymbol{\xi}))^{-1} (\mathbf{y}_i - \mathbf{X}_i \hat{\boldsymbol{\beta}}) \right] \end{aligned} \quad (4.16)$$

As in case of multivariate meta-analysis, likelihood estimators requires iterative algorithms in optimizing the functions 4.15 and 4.16. In particular, the Nelder-Mead method can be employed to find the maximum for the parameters in the multidimensional domain. For ease of computation, both likelihoods are expressed as function of only the $\boldsymbol{\xi}$ parameters, which corresponds to the elements of the lower triangular Cholesky decomposition of $\boldsymbol{\Psi}$. The algorithms start with an initial guess for $\boldsymbol{\Psi}$, obtain an estimate for $\boldsymbol{\beta}$ using GLS estimators and maximize the objective function in terms of $\boldsymbol{\xi}$. The steps are iterated until convergence.

Test of hypothesis and confidence intervals are based on the established theory for mixed models. Inference on the fixed-effects coefficients is conducted in a similar way as presented in section 2.3.2, using the asymptotic normal distribution for the estimator of $\boldsymbol{\beta}$. Tests for the variance components, instead, generally require a mixture of χ^2 because the coefficients to be tested can only be positive. When $p \geq 2$, however, the distribution of the test statistic is difficult to implement, so that alternative measures can be instead applied. Following the idea behind the definition of the Intraclass Correlation Coefficient (ICC), the marginal variance in 4.13 can also be decomposed in the within-study and between-studies components. The dose-response model 4.12 is a mixed model with random-effects for the slope terms and with no intercept.

Thus, the between-studies variance is a quadratic function of the assigned dose values. For this setting Goldstein *et al.* (2002) defined the Variance Partition Coefficient (VPC) as the ratio of the between-studies component by the total residual variability

$$\text{VPC}_{ij} = \frac{\mathbf{z}_{ij} \boldsymbol{\Psi} \mathbf{z}_{ij}^\top}{\mathbf{z}_{ij} \boldsymbol{\Psi} \mathbf{z}_{ij}^\top + s_{ij}^2} \quad (4.17)$$

The VPC is indexed by both i and j because it depends both on the observed dose value z_{ij} and the variance for the log relative risk s_{ij}^2 . Values for VPC can be expressed as percentage to quantify the proportion of residual variance attributable to heterogeneity. Because the VPC will typically vary for different doses, overlay a LOWESS smother in a scatter plot VPC versus dose levels may help to examine the impact of heterogeneity over the exposure range.

4.5.3 Prediction

Predictions for the combined, or marginal, curve are obtained as in equation 2.26, where now the $\hat{\boldsymbol{\beta}}$ coefficients were estimated using the log relative risks as outcome variables rather than the study-specific $\hat{\boldsymbol{\beta}}_i$.

Predictions are also available for study-specific curves. Using the normality distribution for the random-effects, Henderson *et al.* (1959) compute the asymptotic best linear unbiased prediction (BLUP) of the random-effects \mathbf{b} as

$$\hat{\mathbf{b}}_i = \hat{\boldsymbol{\Psi}} \mathbf{Z}_i^\top \hat{\boldsymbol{\Sigma}}_i^{-1} (\mathbf{y}_i - \mathbf{X}_i \hat{\boldsymbol{\beta}}) \quad (4.18)$$

The conditional dose–response coefficients are defined as $\mathbf{X}_i \hat{\boldsymbol{\beta}} + \hat{\mathbf{b}}_i$. Of note, individual curves defined by p parameters can be predicted for those studies reporting $J_i < p$ non-referent relative risks. The BLUP employ the information of the entire distribution of the random-effects to make the best possible prediction.

4.5.4 Comparison with two-stage analysis

Previous methodological articles have oftentimes implemented new methods using the two-stage approach, mainly because of computation reasons. The alternative one-stage approach has been frequently referred to as equivalent and was no further investigated. The tools to assess the goodness-of-fit in Paper II were established using the one-stage framework. We proved in the supplementary material that the two techniques give identical results in a fixed-effects analysis of non-linear curves, not only for the simpler case of a linear trend. In the appendix of Paper V, we extended the equivalence to the setting of non-linear curves for a random-effects model. In order to provide the same point and interval estimates, the study-specific models in the two-stage analysis need to be estimable, i.e. $p \leq \min(J_i)$. In practical examples, small discrepancies in $\hat{\boldsymbol{\beta}}$ and $\widehat{\text{Var}}(\hat{\boldsymbol{\beta}})$ may be related to differences in the optimization methods for the objective functions of the two techniques.

Chapter 5

Results

We illustrate the usage of the developed methodologies and measures reanalyzing data from published dose–response meta-analyses.

5.1 Paper I

The aim of Paper I was to describe the implementation of the two-stage approach for dose–response meta-analysis in the **dosresmeta** R package. We demonstrate the main aspects of the methodology reanalyzing aggregated dose–response data from 21 prospective studies on the association between coffee consumption (cups/day) and all-cause mortality (Crippa *et al.*, 2014). The data set `coffee_mort` is included in the package, with the first six lines printed below.

```
R> library(dosresmeta)
R> data("coffee_mort")
R> head(coffee_mort)
```

	id	author	year	type	dose	cases	n	logrr	se	gender	area
1	1	LeGrady et al.	1987	ci	0.5	57	249	0.0000000	0.0000000	M	USA
2	1	LeGrady et al.	1987	ci	2.5	136	655	-0.2876821	0.1391187	M	USA
3	1	LeGrady et al.	1987	ci	4.5	144	619	-0.1743534	0.1373198	M	USA
4	1	LeGrady et al.	1987	ci	6.5	115	387	0.0861777	0.1401409	M	USA
5	2	Rosengren et al.	1991	ci	0.0	17	192	0.0000000	0.0000000	M	Europe
6	2	Rosengren et al.	1991	ci	1.5	88	1121	-0.1203576	0.2531537	M	Europe

5.1.1 Single study analysis

We show how to estimate the dose–response association in a single study. For that purpose, we select the first study ID 1 consisting of 3 non-referent log relative risks (LeGrady *et al.*, 1987). One relevant feature of aggregated dose–response data is the correlation arising from having a common comparator. The `covar.logrr` function can be used to reconstruct the covariance matrix using the method by Greenland and Longnecker (1992).

```
R> legrady <- subset(coffee_mort, id == 1)
R> covar.logrr(cases = cases, n = n, y = logrr, v = I(se^2), type = type,
+             data = legrady)
              [,1]      [,2]      [,3]
[1,] 0.01935402 0.01279718 0.01259433
[2,] 0.01279718 0.01885673 0.01254856
[3,] 0.01259433 0.01254856 0.01963947
```

The alternative method by Hamling *et al.* (2008) can be used by specifying `covariance = "h"` in the `covar.logrr` function. The reconstructed covariance matrix is used to efficiently estimate the dose-response association. For example, a linear trend $y_{1j} = \beta_1(x_{1j} - x_{10})$ can be estimated with

```
R> lin_le <- dosresmeta(logrr ~ dose, se = se, type = type, cases = cases,
+                     n = n, data = legrady)
R> lin_le
Call: dosresmeta(formula = logrr ~ dose, type = type, cases = cases,
                  n = n, data = legrady, se = se)
```

Fixed-effects coefficients:

```
dose
0.0328
```

```
1 study 3 values, 1 fixed and 0 random-effects parameters
logLik      AIC      BIC
-0.7914    3.5827    2.6813
```

The change in the log relative risk of all-cause mortality associated with a 1 cup/day increase in coffee consumption was 0.033. The interpretation is easier on the exponential scale: every 1 cup/day increase was associated with a 3.4% ($\exp(0.033) = 1.034$) higher mortality risk. The `predict` method facilitates the computation for the predicted linear increase for any arbitrary amount of coffee consumption. For example, setting `delta = 3`

```
R> predict(lin_le, delta = 3, expo = TRUE)
delta    pred    ci.lb    ci.ub
3 1.103507 0.9744976 1.249596
```

every 3 cups/day increase in coffee consumption was associated with a 10% (95% CI: 0.97, 1.25) higher mortality risk.

Alternative curves can be specified in the `formula` argument. For example, a quadratic trend $y_{1j} = \beta_1(x_{1j} - x_{10}) + \beta_2(x_{1j}^2 - x_{10}^2)$ can be estimated.

```
R> quadr_le <- dosresmeta(logrr ~ dose + I(dose^2), se = se, type = type,
+                       cases = cases, n = n, data = legrady)
R> quadr_le
Call: dosresmeta(formula = logrr ~ dose + I(dose^2), type = type, cases = cases,
                  n = n, data = legrady, se = se)
```


Fixed-effects coefficients:

```
      dose I(dose^2)
-0.2135    0.0334
```

1 study 3 values, 2 fixed and 0 random-effects parameters

```
logLik      AIC      BIC
3.5738 -3.1475 -4.9503
```

The coefficients of the quadratic model are not directly interpretable. The results can be instead presented in terms of predicted relative risk for select values of coffee consumption.

```
R> predict(quadr_le, newdata = data.frame(dose = 0:6), expo = TRUE)
      dose I(dose^2)      pred      ci.lb      ci.ub
1      0          0 1.0000000 1.0000000 1.0000000
2      1          1 0.8352219 0.7209175 0.9676497
3      2          4 0.7458585 0.5796705 0.9596916
4      3          9 0.7121374 0.5191844 0.9768005
5      4         16 0.7269823 0.5166453 1.0229519
6      5         25 0.7934812 0.5680037 1.1084654
7      6         36 0.9259812 0.6805480 1.2599276
```

5.1.2 Multiple studies

The chosen curves can be estimated also for the other studies. One possibility is to use the **tidyverse** package in order to obtain the linear trends and corresponding variances

```
R> library(tidyverse)
R> lin_i <- coffee_mort %>%
+   split(.$id) %>%
+   map(~ dosresmeta(logrr ~ dose, se = se, type = type,
+                     cases = cases, n = n, data = .x))
R> lin_bi <- map_dbl(lin_i, ~ coef(.x))
R> lin_vi <- map_dbl(lin_i, ~ vcov(.x))
R> head(cbind(bi = lin_bi, vi = lin_vi))
      bi      vi
1 0.03283124 4.470869e-04
2 -0.02360445 3.561441e-04
3 -0.01430817 5.833618e-05
4 -0.04777017 6.194806e-04
5 -0.04736154 1.219069e-03
6 -0.02027627 1.127937e-04
```

The mean linear trend can be calculated with standard packages for meta-analysis such as the **mvmeta** package

```
R> mvmeta(lin_bi, lin_vi)
Call: mvmeta(formula = lin_bi ~ 1, S = lin_vi)
```

Fixed-effects coefficients:

```
(Intercept)
  -0.0326
```

22 studies, 22 observations, 1 fixed and 1 random-effects parameters

```
logLik      AIC      BIC
36.0221 -68.0442 -65.9551
```

Alternatively, the two steps of a two-stage analysis (dose–response analysis and pooling) are unified and simplified in the `dosresmeta` function. In a single call, the study-specific linear trends are estimated and combined with the results being stored in the `lin` object.

```
R> lin <- dosresmeta(logrr ~ dose, id = id, se = se, type = type,
+                   cases = cases, n = n, data = coffee_mort)
```

The summary method displays the measures and tests of interest

```
R> summary(lin)
```

```
Call: dosresmeta(formula = logrr ~ dose, id = id, type = type, cases = cases,
  n = n, data = coffee_mort, se = se)
```

Two-stage random-effects meta-analysis

Estimation method: REML

Covariance approximation: Greenland & Longnecker

Chi2 model: X2 = 41.8314 (df = 1), p-value = 0.0000

Fixed-effects coefficients

	Estimate	Std. Error	z	Pr(> z)	95%ci.lb	95%ci.ub
(Intercept)	-0.0326	0.0050	-6.4677	0.0000	-0.0424	-0.0227

Between-study random-effects (co)variance components

```
Std. Dev
  0.0172
```

Univariate Cochran Q-test for residual heterogeneity:

Q = 77.0088 (df = 21), p-value = 0.0000

I-square statistic = 72.7%

22 studies, 22 values, 1 fixed and 1 random-effects parameters

```
logLik      AIC      BIC
36.0221 -68.0442 -65.9551
```

There was an inverse association between increasing levels of coffee consumption and all-cause mortality risk, with a mean relative risk of $\exp(-0.03) = 0.97$ for a 1 cup/day increase. Similarly to the single study analysis, the `predict` function returns the combined result for any amount of coffee consumption.

```
R> predict(lin, delta = 3, expo = T)
delta      pred      ci.lb      ci.ub
3 0.9069412 0.8804891 0.9341879
```

The linear trend appeared to be heterogeneous as indicated by both the Q test ($Q = 77$, p value < 0.01) and $I^2 = 73$. A possible alternative for both reducing the observed heterogeneity and relaxing the linearity assumption is to model the dose–response as a quadratic curve.

```
R> quadr <- dosresmeta(logrr ~ dose + I(dose^2), id = id, se = se, type = type,
+                      cases = cases, n = n, data = coffee_mort)
R> summary(quadr)
Call: dosresmeta(formula = logrr ~ dose + I(dose^2), id = id, type = type,
                  cases = cases, n = n, data = coffee_mort, se = se)
```

Two-stage random-effects meta-analysis
 Estimation method: REML
 Covariance approximation: Greenland & Longnecker

Chi2 model: $X^2 = 75.9675$ (df = 2), p -value = 0.0000

Fixed-effects coefficients

	Estimate	Std. Error	z	Pr(> z)	95%ci.lb	95%ci.ub
dose.(Intercept)	-0.0847	0.0138	-6.1315	0.0000	-0.1118	-0.0576
I(dose^2).(Intercept)	0.0095	0.0023	4.1751	0.0000	0.0050	0.0139

Between-study random-effects (co)variance components

	Std. Dev	Corr
dose	0.0491	dose
I(dose^2)	0.0081	-0.9811

Univariate Cochran Q-test for residual heterogeneity:

$Q = 113.4826$ (df = 42), p -value = 0.0000
 I-square statistic = 63.0%

22 studies, 44 values, 2 fixed and 3 random-effects parameters

	logLik	AIC	BIC
	96.2340	-182.4680	-173.7796

The overall test $H_0 : \beta_1 = \beta_2 = 0$ (Chi2 model) indicated that the mortality risk significantly varies according to coffee consumption levels. The quadratic model reduces to the simpler linear trend analysis when $\beta_2 = 0$. Thus, the univariate test for β_2 ($z = 4.18$, p value < 0.01) suggested that the all-cause mortality risk is related in a non-linear fashion with coffee consumption. The heterogeneity in the study-specific regression coefficients reduced but its impact was still important, with the multivariate $I^2 = 63\%$.

The predicted log relative risks from the linear and quadratic analysis can be presented in a graphical format using $x_{\text{ref}} = 0$ cups/day as referent (figure 5.1).

```
R> xref <- 0
R> pred <- data.frame(dose = c(xref, seq(0, 8, .1))) %>%
+   predict(quadr, newdata = ., expo = T) %>%
+   cbind(lin = predict(lin, newdata = ., expo = T))
R> ggplot(pred, aes(dose, pred, ymin = ci.lb, ymax = ci.ub)) +
+   geom_line() + geom_ribbon(alpha = .1) +
+   geom_line(aes(y = lin.pred), linetype = "dashed") +
+   scale_y_continuous(trans = "log", breaks = scales::pretty_breaks()) +
+   labs(x = "Coffee consumption (cups/day)", y = "Relative Risk")
```

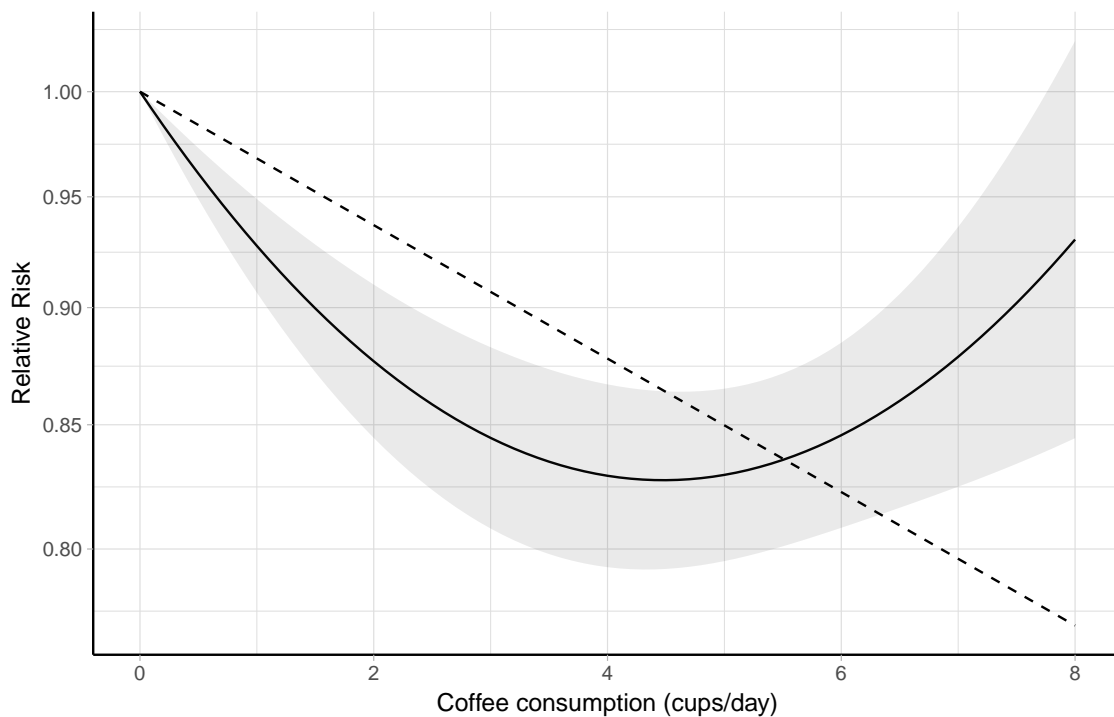


Figure 5.1: Combined dose-response association between coffee consumption and all-cause mortality (solid line) with 95% confidence intervals (shaded area). Coffee consumption was modelled with a quadratic curve in a two-stage random-effects meta-analysis. Dashed line represents the combined linear trend. The value 0 cups/day serves as referent. The relative risks are plotted on the log scale.

Alternatively, the predicted relative risks for desired exposure values, say from 0 to 5 cups/day can be presented in a table

```
R> filter(pred, dose %in% 0:5) %>%
+   select(`-I(dose^2)`, -lin.dose) %>%
+   unique() %>% round(3)
  dose pred ci.lb ci.ub lin.pred lin.ci.lb lin.ci.ub
1    0 1.000 1.000 1.000   1.000   1.000   1.000
3    1 0.928 0.907 0.949   0.968   0.958   0.978
4    2 0.877 0.845 0.910   0.937   0.919   0.956
5    3 0.845 0.808 0.883   0.907   0.880   0.934
6    4 0.829 0.793 0.867   0.878   0.844   0.913
7    5 0.829 0.795 0.865   0.850   0.809   0.893
```

The previous predictions can be easily re-expressed using a different exposure value such as 1.5 cup/day by changing `xref <- 1.5` and rerunning the previous code to produce a new figure or table.

The study-specific dose–response coefficients and related covariance matrices are stored in the results and can be easily accessed. For example, the $\hat{\beta}_i$ and $\widehat{\text{Var}}(\hat{\beta}_i)$ for the quadratic model in the first two studies are

```
R> quadr$bi[1:2, ]
      dose      I(dose^2)
1 -0.213506072  0.033448197
2 -0.008546787 -0.001605319
R> quadr$Si[1:2]
[[1]]
      [,1]      [,2]
[1,]  0.0073978648 -0.0009437912
[2,] -0.0009437912  0.0001281500

[[2]]
      [,1]      [,2]
[1,]  0.0043603384 -4.268928e-04
[2,] -0.0004268928  4.551165e-05
```

and can be used to plot the individual curves in figure 5.2.

```
R> newd <- data.frame(dose = c(xref, seq(0, 6, .1)))
R> newd %>%
+   cbind(map(array_branch(quadr$bi, 1), ~ exp(.x[1]*newd$dose + .x[2]*newd$dose^2))) %>%
+   gather(study, pred, -dose) %>%
+   ggplot(aes(dose, pred, group = study)) + geom_line() +
+   scale_y_continuous(trans = "log", breaks = c(.5, 1, 2, 5, 10), limits = c(.25, 10)) +
+   labs(x = "Coffee consumption (cups/day)", y = "Relative Risk")
```

5.2 Paper II

We use the tools presented in section 4.2 to evaluate the goodness-of-fit of the previous analyses. The `gof` function returns a display of the quantities of interest, namely the deviance test and the adjusted and unadjusted R^2 . We started with the simpler linear trend estimated in a fixed-effect analysis.

```
R> gof(lin, fixed = TRUE)
Goodness-of-fit statistics:

Deviance test:
D = 225.244 (df = 78), p-value = 0.000

Coefficient of determination R-squared: 0.488
Adjusted R-squared: 0.482
```

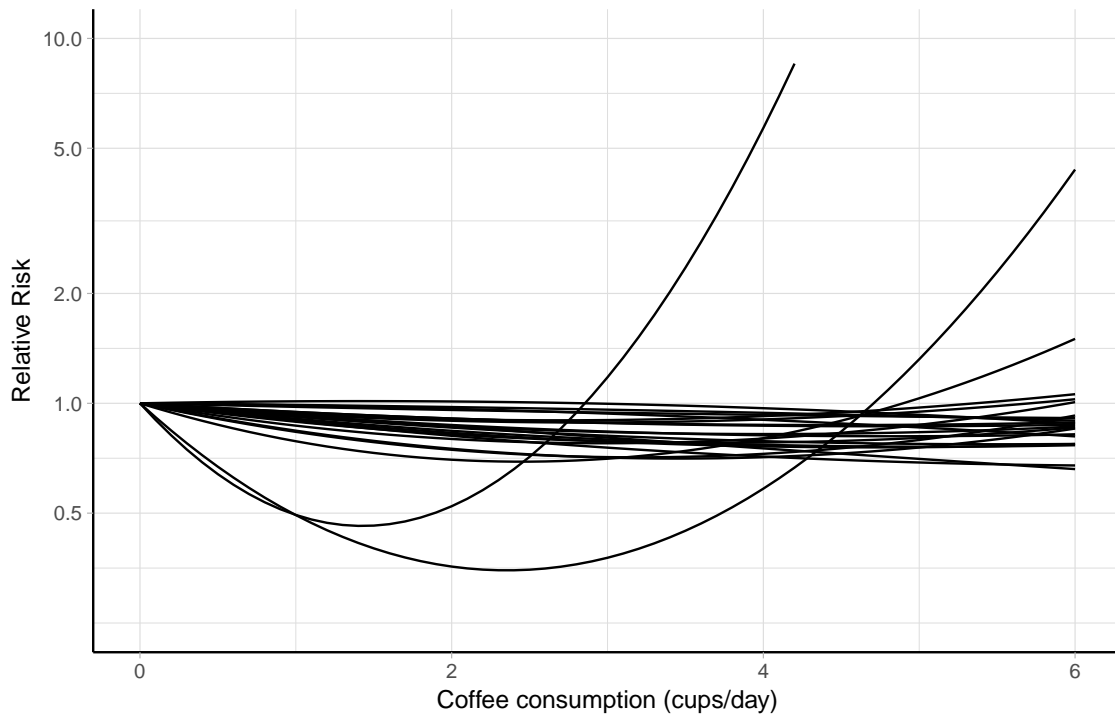


Figure 5.2: Study-specific quadratic associations between coffee consumption and all-cause mortality. The relative risks are presented on a log scale using 0 cups/day as referent.

The fit for the model assuming a linear relationship was poor (analysis A in table 5.1). In particular, the deviance test rejected the null hypothesis that the model was properly specified ($D = 225.2$, p value < 0.001) while the percentage of the accounted variation by the analysis was 49%. In addition, the decorrelated residuals vs exposure plot in panel A of figure 5.3 indicated a specific pattern with negative residuals for low values of the exposure (before 5 cups/day) and positive ones for high levels of coffee consumption.

A possible solution for addressing the lack of fit of the previous analysis is to consider a non-linear example such as a quadratic curve (analysis B). The fit slightly improved as indicated by R^2 which increased to 65% ($R^2_{\text{adj}} = 0.64$). The deviance test, however, still showed evidence of lack of fit ($D = 155.1$, p value < 0.001). Furthermore, even if the variability of the residuals around reduced (panel B of figure 5.3), the LOWESS smoother showed again a tendency to be more likely positive for low and extreme high exposure values.

An alternative strategy (analysis C) was to model coffee consumption using RCS with 3 knots located at the fixed quantiles 0.10, 0.5, and 0.9 corresponding to 0, 2, 6.5 cups/day. Since the number of parameters is the same as in the analysis B ($p = 2$), the R^2 can be used to compare the fit of the two strategies. In particular, the RCS analysis had a better fit, as indicated by the higher $R^2 = 0.68$ ($R^2_{\text{adj}} = 0.67$). The pattern in the residuals was also leveled off around zero with the exception for the 3 highest dose levels. The deviance test, however, rejected again the null hypothesis for model specification, possibly because of the heterogeneity in the individual curves.

To address this variability, we employed meta-regression models to explain differences

across the studies (analysis D). We included two study-level covariates indicating the geographical area where the study was conducted (Europa, USA, and Japan) and the sex of the participants (only men, only women, and both sexes). Both the decorrelated vs exposure plot and $R^2_{\text{adj}} = 0.74$ indicated an improvement in the overall fit of the analysis even if the p value for the deviance test was below the nominal value ($D = 100.4$, p value = 0.008).

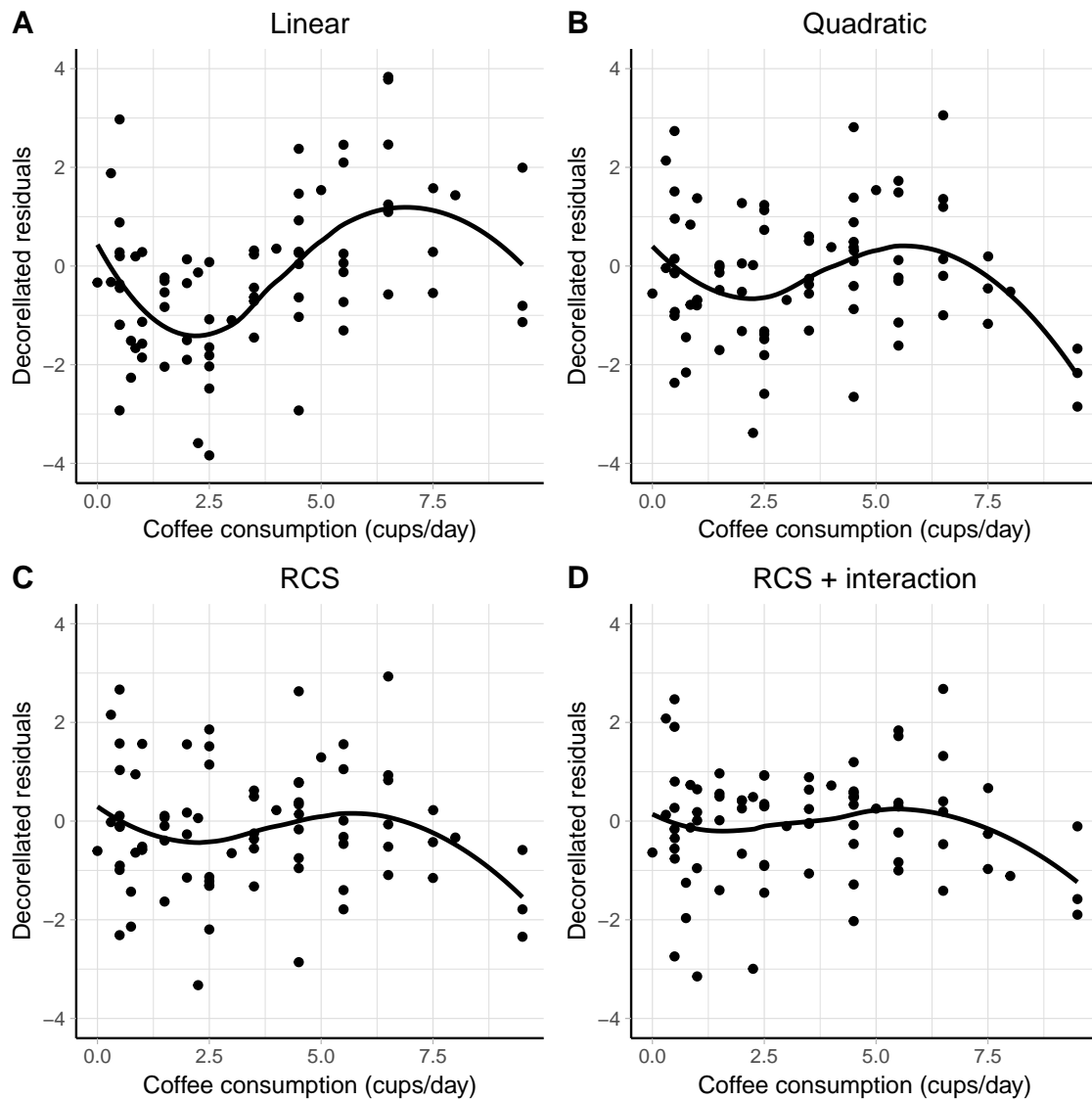


Figure 5.3: Decorrelated residuals versus exposure plots with LOWESS smoother for different modelling strategies in a dose–response meta-analysis between coffee consumption and all-cause mortality (Crippa *et al.*, 2014)

5.3 Paper III

The aim of Paper III was to develop an alternative measure of heterogeneity for meta-analysis that did not depend on the distribution of the within-study error terms. We illustrate how to employ the new measure reanalyzing aggregated dose–response data on the association

Table 5.1: Goodness-of-fit tests and measures for dose-response meta-analysis of coffee consumption and all-cause mortality (Crippa *et al.*, 2014)

Analysis	Model	Deviance	df	<i>p</i> value	R^2	R^2_{adj}
A	Linear	225.244	78	0.000	0.488	0.482
B	Quadratic	155.093	77	0.000	0.648	0.638
C	RCS ^a	141.332	77	0.000	0.679	0.671
D	RCS + interaction ^b	100.372	69	0.008	0.772	0.739

^a 3 knots located at the 10th, 50th, and 90th percentiles of the distribution of coffee.

^b As in c) + interaction with gender of participants (only men, only women, both sexes) and geographical area (Europe, USA, Japan) included as categorical study-level covariates.

between meat and bladder cancer (Crippa *et al.*, 2016b). Five cohort and 8 case-control studies reported results for either red or processed meat and bladder cancer risk including a total of 10,271 cases and 1,066,027 participants. The data for both the associations are also included in the *dosresmeta* package.

5.3.1 Processed meat and bladder cancer

We started considering a linear trend analysis for the association between processed meat and bladder cancer risk. The effect sizes for the meta-analysis in the second part of a two-stage dose-response meta-analysis were the linear trends for a 50 g per day increase in processed meat consumption (figure 5.4). The combined relative risk was 1.2 (95% CI 1.06, 1.37). The *Q* test provided some indication of presence of statistical heterogeneity ($Q = 17.2$, p value = 0.07). The $\hat{R}_b = 38\%$ (95% CI 37, 40) indicated that the contribution of heterogeneity in the pooled analysis was limited (table 1), as also suggested by the alternative measures $I^2 = 42\%$ (95% CI 40, 43) and $R_I = 43\%$ (95% CI 41, 44). Because the within-study variances were substantial homogenous the differences between the alternative measures were negligible.

No evidence of non-linearity was observed using either a quadratic curve (p value = 0.96) or a RCS model with 3 knots located at fixed percentiles (p value = 0.923).

5.3.2 Red meat and bladder cancer

An analogous analysis was conducted for the association between red meat consumption and bladder cancer risk, with the estimated linear trends expressed for a 100 g per day increase. The pooled relative risk was 1.22 (95% CI 1.05, 1.41). The study-specific associations in figure 5.5, however, appeared to be heterogeneous ($Q = 60$, p value < 0.01). In particular, the contribution of the heterogeneity in determining the variance of the combined effect was $\hat{R}_b = 67\%$, indicating a moderate impact. Given that the distribution of within-error terms was higher as compared to the previous analysis (figure A.1), the differences with the alternative measures were substantially higher: $I^2 = 80\%$ (95% CI 79, 81) and $R_I = 89\%$ (95% CI 88, 89), which suggested a larger impact of the heterogeneity.

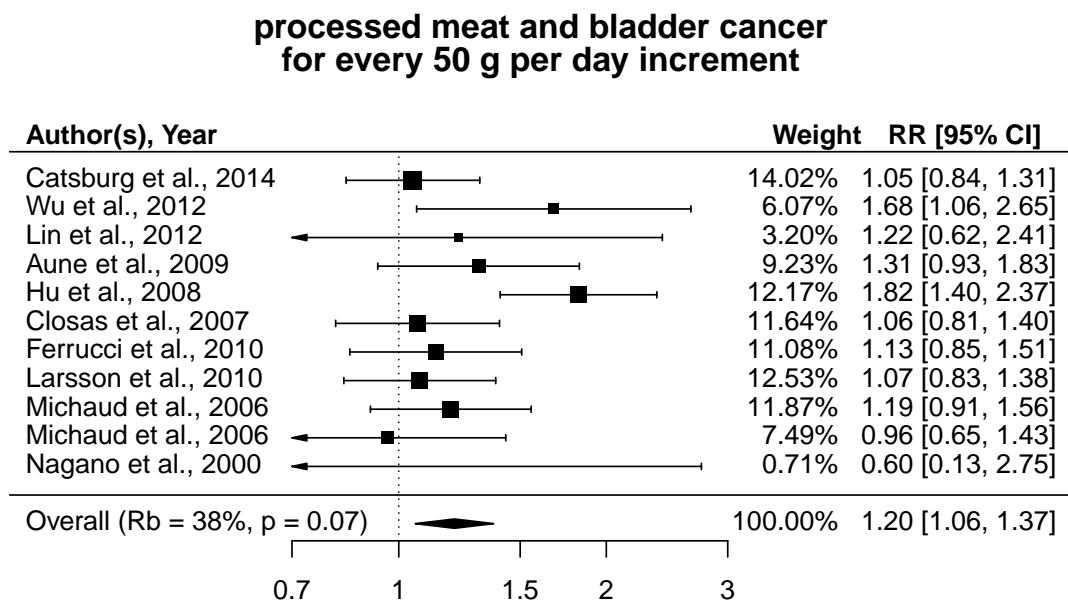


Figure 5.4: Relative risks of bladder cancer for every 50 g increase per day in processed meat consumption

Similarly to the case of processed meat, no evidence of non-linearity was found (p value equal to 0.73 and 0.74 for β_2 in the quadratic and RCS model.)

The variability across the linear trends could be related to differences in the study design. Figure 5.5 reports also the results separately for cohort and case-control studies. No association was observed in the subset of the prospective studies (combined $RR = 1.01$ (95% CI 0.97, 1.06)). The individual associations were homogenous ($Q = 3.5$, p value = 0.62), with $\hat{R}_b = 38\%$. The results for case-control studies, instead, largely varied across studies $Q = 39.8$, p value < 0.01 and $\hat{R}_b = 81\%$. A summary of the results for the alternative measures of heterogeneity in the different analyses is presented in table 5.2.

5.4 Paper IV

Table 5.2: Measures of heterogeneity for dose-response meta-analysis between processed and red meat and bladder cancer risk (Crippa *et al.*, 2016b)

Analysis	$\hat{\beta}$ (95% CI)	Q test, p values	CV_{V_i}	\hat{R}_b (95% CI)	I^2 (95% CI)	\hat{R}_I (95% CI)
Processed meat	1.2 (1.06, 1.37)	17, 0.07	0.33	38 (37, 40)	42 (40, 43)	43 (41, 44)
Red meat	1.22 (1.05, 1.41)	60, < 0.01	5.94	67 (66, 68)	80 (79, 81)	89 (88, 89)
Red meat Case-control	1.01 (0.97, 1.06)	4, 0.6	3.51	0 (0, 4)	0 (0, 8)	0 (0, 100)
Red meat Prospective	1.51 (1.13, 2.02)	40, < 0.01	0.36	81 (80, 82)	85 (84, 86)	86 (85, 86)

Red meat and bladder cancer for every 100 g per day increment

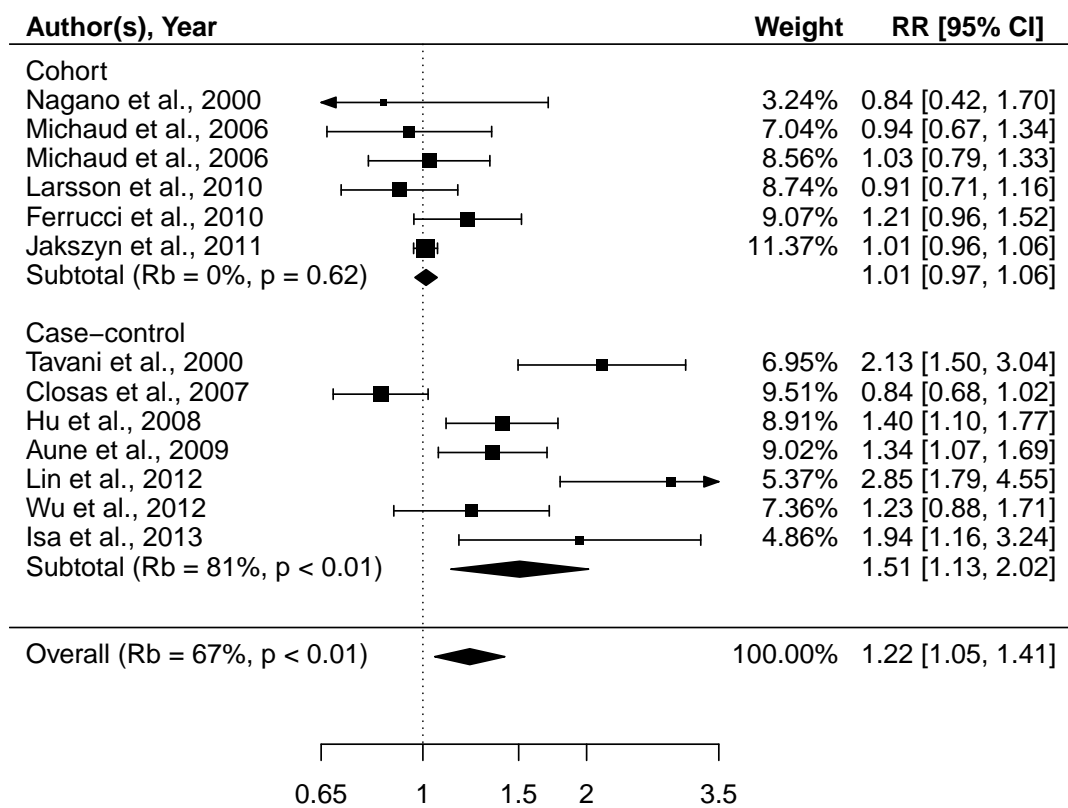


Figure 5.5: Relative risks of bladder cancer for every 50 g increase per day in red meat consumption separately for cohort and case-control studies

Chapter 6

Discussion

Write the discussion with subsections as in the background section

Chapter 7

Conclusions

The methods presented in this thesis enrich the set of tools available for applying dose–response meta-analyses and for addressing specific questions including how to evaluate the goodness-of-fit and how to measure the impact of the between-studies heterogeneity. Furthermore, this thesis describes alternative models for pooling results in case of heterogeneous exposure range and for estimating complex models without excluding relevant studies. The proposed methods have been illustrated using real data from published meta-analyses and implemented in the `dosresmeta` and `hetmeta` R packages available on CRAN.

More specifically we conclude the following:

- The `dosresmeta` R package can help practitioners to conduct dose–response meta-analyses and to apply the methods presented in this thesis. Dedicated functions help to avoid pitfalls frequently encountered in published meta-analyses, such as definition of the design matrix and prediction of the pooled results (Paper I).
- Goodness-of-fit should be regularly evaluated in applied dose–response meta-analysis. The proposed solutions consist of descriptive measures to summarize the agreement between fitted and observed data (the deviance and the coefficient of determination), and graphical tools to visualize the fit of the model (decorrelated residuals-versus-exposure plot). These tools can be employed to identify systematic dose–response patterns and possible source of heterogeneity, and to support the conclusions in applied meta-analyses (Paper II).
- The new measure of heterogeneity, R_b , quantifies the proportion of the variance of the pooled estimate attributable to the between-study heterogeneity. Contrary to the available measures of heterogeneity, it does not make any assumption about the distribution of the within-study error variances, nor does it require specification of a typical value for these quantities. Therefore, we recommend the use of the R_b as preferred measure for quantifying the impact of heterogeneity (Paper III).
- A point-wise strategy for dose–response meta-analysis does not require the specification of a unique model as in the traditional approaches, and therefore allows for more flexibility in modeling the individual curves. In addition, the extent of extrapolation is limited

by predicting the study-specific relative risk based on the observe exposure range. The use of the described strategy may improve the robustness of the results, especially in case of heterogeneous exposure range (Paper IV).

- A one-stage approach for dose–response meta-analysis consists of a linear mixed-effects model, which offer useful tools for describing the impact of heterogeneity over the exposure range, for comparing the fit of different models, and for predicting individual dose–response associations. Thhe main advantage is that flexible curves can be estimated regardless of the number of data-points in the individual analyses (Paper V).

Chapter 8

Future research

Based on the conclusions presented in this thesis, future research includes:

- <>
- <>
- <>

Appendix A

Supplementary figures

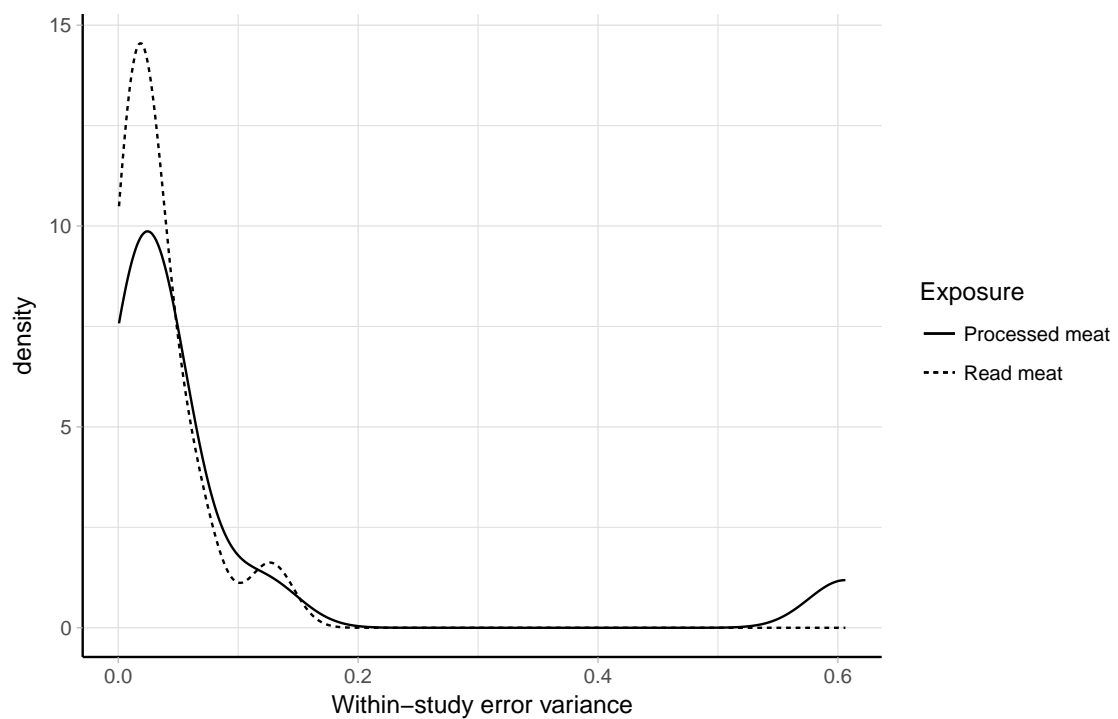


Figure A.1: Estimated distribution for within-error terms in a dose-response meta-analysis between processed and red meat and bladder cancer risk (Crippa *et al.*, 2016b)

Appendix B

Supplementary tables

Tables.

References

- Bagnardi V, Zambon A, Quatto P, Corrao G (2004). "Flexible meta-regression functions for modeling aggregate dose-response data, with an application to alcohol and mortality." *American journal of epidemiology*, **159**(11), 1077–1086.
- Berkey C, Anderson J, Hoaglin D (1996). "Multiple-outcome meta-analysis of clinical trials." *Statistics in medicine*, **15**(5), 537–557.
- Berkey C, Hoaglin D, Antczak-Bouckoms A, Mosteller F, Colditz G (1998). "Meta-analysis of multiple outcomes by regression with random effects." *Statistics in medicine*, **17**(22), 2537–2550.
- Berkey CS, Hoaglin DC, Mosteller F, Colditz GA (1995). "A random-effects regression model for meta-analysis." *Statistics in medicine*, **14**(4), 395–411.
- Berlin JA, Longnecker MP, Greenland S (1993). "Meta-analysis of epidemiologic dose-response data." *Epidemiology*, **4**(3), 218–228.
- Berrington A, Cox D (2003). "Generalized least squares for the synthesis of correlated information." *Biostatistics*, **4**(3), 423–431.
- Biggerstaff B, Tweedie R (1997). "Incorporating variability in estimates of heterogeneity in the random effects model in meta-analysis." *Statistics in medicine*, **16**(7), 753–768.
- Borenstein M, Hedges LV, Higgins J, Rothstein HR (2009). *References*. Wiley Online Library.
- Borenstein M, Hedges LV, Higgins J, Rothstein HR (2010). "A basic introduction to fixed-effect and random-effects models for meta-analysis." *Research synthesis methods*, **1**(2), 97–111.
- Buse A (1973). "Goodness of fit in generalized least squares estimation." *The American Statistician*, **27**(3), 106–108.
- Cochran WG (1954). "The combination of estimates from different experiments." *Biometrics*, **10**(1), 101–129.
- Colditz GA, Burdick E, Mosteller F (1995). "Heterogeneity in meta-analysis of data from epidemiologic studies: a commentary." *American journal of epidemiology*, **142**(4), 371–382.
- Crippa A, Discacciati A, Bottai M, Spiegelman D, Orsini N (2018a). "One-stage dose-response meta-analysis for aggregated data." *Manuscript*.

- Crippa A, Discacciati A, Larsson SC, Wolk A, Orsini N (2014). "Coffee consumption and mortality from all causes, cardiovascular disease, and cancer: a dose-response meta-analysis." *American journal of epidemiology*, **180**(8), 763–775.
- Crippa A, Khudyakov P, Wang M, Orsini N, Spiegelman D (2016a). "A new measure of between-studies heterogeneity in meta-analysis." *Statistics in medicine*, **35**(21), 3661–3675.
- Crippa A, Larsson SC, Discacciati A, Wolk A, Orsini N (2016b). "Red and processed meat consumption and risk of bladder cancer: a dose-response meta-analysis of epidemiological studies." *European journal of nutrition*, pp. 1–13.
- Crippa A, Orsini N (2016a). "Dose-response meta-analysis of differences in means." *BMC medical research methodology*, **16**(1), 91.
- Crippa A, Orsini N (2016b). "Multivariate dose-response meta-analysis: The dosresmeta R Package." *Journal of statistical software, Code Snippets*, **72**(1), 1–15. doi:10.18637/jss.v072.c01.
- Crippa A, Thomas I, Orsini N (2018b). "A pointwise approach to dose-response meta-analysis of aggregated data." *Submitted*.
- De Boor C, De Boor C, Mathématicien EU, De Boor C, De Boor C (1978). *A practical guide to splines*, volume 27. Springer-Verlag New York.
- DerSimonian R, Laird N (1986). "Meta-analysis in clinical trials." *Controlled clinical trials*, **7**(3), 177–188.
- Discacciati A, Crippa A, Orsini N (2015). "Goodness of fit tools for dose-response meta-analysis of binary outcomes." *Research synthesis methods*.
- Draper NR, Smith H (2014). *Applied regression analysis*. John Wiley & Sons.
- Easton DF, Peto J, Babiker AG (1991). "Floating absolute risk: an alternative to relative risk in survival and case-control analysis avoiding an arbitrary reference group." *Statistics in medicine*, **10**(7), 1025–1035.
- Gasparrini A, Armstrong B, Kenward M (2012). "Multivariate meta-analysis for non-linear and other multi-parameter associations." *Statistics in medicine*, **31**(29), 3821–3839.
- Goldstein H, Browne W, Rasbash J (2002). "Partitioning variation in multilevel models." *Understanding Statistics: Statistical Issues in Psychology, Education, and the Social Sciences*, **1**(4), 223–231.
- Greenland S (1995). "Dose-response and trend analysis in epidemiology: alternatives to categorical analysis." *Epidemiology*, pp. 356–365.

- Greenland S, Longnecker MP (1992). "Methods for trend estimation from summarized dose-response data, with applications to meta-analysis." *American journal of epidemiology*, **135**(11), 1301–1309.
- Hagquist C, Stenbeck M (1998). "Goodness of fit in regression analysis—R² and G² reconsidered." *Quality and Quantity*, **32**(3), 229–245.
- Haidich AB (2010). "Meta-analysis in medical research." *Hippokratia*, **14**(Suppl 1), 29.
- Hamling J, Lee P, Weitkunat R, Ambühl M (2008). "Facilitating meta-analyses by deriving relative effect and precision estimates for alternative comparisons from a set of estimates presented by exposure level or disease category." *Statistics in medicine*, **27**(7), 954–970.
- Harrell Jr FE (2015). *Regression modeling strategies: with applications to linear models, logistic and ordinal regression, and survival analysis*. Springer.
- Harville DA (1977). "Maximum likelihood approaches to variance component estimation and to related problems." *Journal of the American Statistical Association*, **72**(358), 320–338.
- Hedges LV (1983). "A random effects model for effect sizes." *Psychological Bulletin*, **93**(2), 388.
- Henderson CR, Kempthorne O, Searle SR, Von Krosigk C (1959). "The estimation of environmental and genetic trends from records subject to culling." *Biometrics*, **15**(2), 192–218.
- Higgins J, Thompson SG (2002). "Quantifying heterogeneity in a meta-analysis." *Statistics in medicine*, **21**(11), 1539–1558.
- Higgins J, Thompson SG, Spiegelhalter DJ (2009). "A re-evaluation of random-effects meta-analysis." *Journal of the Royal Statistical Society: Series A (Statistics in Society)*, **172**(1), 137–159.
- Higgins JP (2008). "Commentary: Heterogeneity in meta-analysis should be expected and appropriately quantified." *International journal of epidemiology*, **37**(5), 1158–1160.
- Jackson D, Riley R, White IR (2011). "Multivariate meta-analysis: Potential and promise." *Statistics in Medicine*, **30**(20), 2481–2498.
- Jackson D, White IR, Riley RD (2012). "Quantifying the impact of between-study heterogeneity in multivariate meta-analyses." *Statistics in medicine*, **31**(29), 3805–3820.
- Jackson D, White IR, Thompson SG (2010). "Extending DerSimonian and Laird's methodology to perform multivariate random effects meta-analyses." *Statistics in medicine*, **29**(12), 1282–1297.
- Kvålseth TO (1985). "Cautionary note about R²." *The American Statistician*, **39**(4), 279–285.

- Langan D, Higgins J, Simmonds M (2017). "Comparative performance of heterogeneity variance estimators in meta-analysis: a review of simulation studies." *Research synthesis methods*, **8**(2), 181–198.
- Larsson SC, Crippa A, Orsini N, Wolk A, Michaëlsson K (2015). "Milk consumption and mortality from all causes, cardiovascular disease, and cancer: a systematic review and meta-analysis." *Nutrients*, **7**(9), 7749–7763.
- Legrady D, Dyer AR, Shekelle RB, Stamler J, Liu K, Paul O, Lepper M, Shryock AM (1987). "Coffee consumption and mortality in the Chicago Western Electric Company study." *American journal of epidemiology*, **126**(5), 803–812.
- Liu Q, Cook NR, Bergström A, Hsieh CC (2009). "A two-stage hierarchical regression model for meta-analysis of epidemiologic nonlinear dose–response data." *Computational Statistics & Data Analysis*, **53**(12), 4157–4167.
- Orsini N, Bellocco R, Greenland S, *et al.* (2006). "Generalized least squares for trend estimation of summarized dose-response data." *Stata Journal*, **6**(1), 40.
- Orsini N, Greenland S, *et al.* (2011a). "A procedure to tabulate and plot results after flexible modeling of a quantitative covariate." *Stata Journal*, **11**(1), 1.
- Orsini N, Li R, Wolk A, Khudyakov P, Spiegelman D (2011b). "Meta-analysis for linear and nonlinear dose-response relations: examples, an evaluation of approximations, and software." *American journal of epidemiology*, **175**(1), 66–73.
- Pinheiro J, Bates D (2010). *Mixed-Effects Models in S and S-PLUS*. Springer Science & Business Media. ISBN 978-1-4419-0318-1.
- Pogue JM, Yusuf S (1997). "Cumulating evidence from randomized trials: utilizing sequential monitoring boundaries for cumulative meta-analysis." *Controlled clinical trials*, **18**(6), 580–593.
- Rice K, Higgins J, Lumley T (2017). "A re-evaluation of fixed effect (s) meta-analysis." *Journal of the Royal Statistical Society: Series A (Statistics in Society)*.
- Ritz J, Demidenko E, Spiegelman D (2008). "Multivariate meta-analysis for data consortia, individual patient meta-analysis, and pooling projects." *Journal of Statistical Planning and Inference*, **138**(7), 1919–1933.
- Royston P, Altman DG (1994). "Regression using fractional polynomials of continuous covariates: parsimonious parametric modelling." *Applied statistics*, pp. 429–467.
- Royston P, Altman DG, Sauerbrei W (2006). "Dichotomizing continuous predictors in multiple regression: a bad idea." *Statistics in medicine*, **25**(1), 127–141.
- Sauerbrei W, Royston P (2011). "A new strategy for meta-analysis of continuous covariates in observational studies." *Statistics in medicine*, **30**(28), 3341–3360.

- Shi JQ, Copas J (2004). "Meta-analysis for trend estimation." *Statistics in medicine*, **23**(1), 3–19.
- Sidik K, Jonkman JN (2005). "Simple heterogeneity variance estimation for meta-analysis." *Journal of the Royal Statistical Society: Series C (Applied Statistics)*, **54**(2), 367–384.
- Sutton AJ, Abrams KR (2001). "Bayesian methods in meta-analysis and evidence synthesis." *Statistical methods in medical research*, **10**(4), 277–303.
- Sutton AJ, Cooper NJ, Jones DR, Lambert PC, Thompson JR, Abrams KR (2007). "Evidence-based sample size calculations based upon updated meta-analysis." *Statistics in medicine*, **26**(12), 2479–2500.
- Sutton AJ, Higgins J (2008). "Recent developments in meta-analysis." *Statistics in medicine*, **27**(5), 625–650.
- Takahashi K, Nakao H, Hattori S (2013). "Cubic spline regression of J-shaped dose-response curves with likelihood-based assignments of grouped exposure levels." *J. Biom. Biostat*, **4**, 1–6.
- Takahashi K, Tango T (2010). "Assignment of grouped exposure levels for trend estimation in a regression analysis of summarized data." *Statistics in medicine*, **29**(25), 2605–2616.
- Takkouche B, Cadarso-Suárez C, Spiegelman D (1999). "Evaluation of old and new tests of heterogeneity in epidemiologic meta-analysis." *American journal of epidemiology*, **150**(2), 206–215.
- Theil H (1958). "Economic forecasts and policy."
- Turner EL, Dobson JE, Pocock SJ (2010). "Categorisation of continuous risk factors in epidemiological publications: a survey of current practice." *Epidemiologic Perspectives & Innovations*, **7**(1), 9.
- Van Houwelingen HC, Arends LR, Stijnen T (2002). "Advanced methods in meta-analysis: multivariate approach and meta-regression." *Statistics in medicine*, **21**(4), 589–624.
- Verbeke G (1997). *Linear mixed models for longitudinal data*. Springer.
- White IR, et al. (2011). "Multivariate random-effects meta-regression: updates to mvmeta." *Stata Journal*, **11**(2), 255.
- Whitehead A, Whitehead J (1991). "A general parametric approach to the meta-analysis of randomized clinical trials." *Statistics in medicine*, **10**(11), 1665–1677.

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