Original article

Mobility and COVID-19 mortality across Scandinavia: A modeling study

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A R T I C L E   I N F O

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A B S T R A C T

Background: In response to COVID-19, the Swedish government imposed few travel and mobility restrictions. This contrasted with its Scandinavian neighbours which implemented stringent restrictions. The influence these different approaches had on mobility, and thus on COVID-19 mortality was investigated.
Methods: Datasets indicating restriction severity and community mobility were examined; Google's 'Community Movement Reports' (CMR) show activity at key location categories; the Oxford COVID-19 Government Response Tracker collates legislative restrictions into a 'Stringency Index' (SI).
Results: CMR mobility categories were negatively correlated with COVID-19 mortality. The strongest correlations were obtained by negatively time lagging mortality data, suggesting restrictions had a delayed influence. During the 'first wave' a model using SI (AIC 632.87) proved favorable to one using contemporaneous CMR data and SI (AIC 1193.84), or lagged CMR data and SI (AIC 642.35). Validation using 'second wave' data confirmed this; the model using SI solely again being optimal (RMSE: 0.2486 vs. 0.522 and 104.62). Cross-country differences were apparent in all models; Swedish data, independent of SI and CMR, proved significant throughout. There was a significant association for Sweden and the death number across models.
Conclusion: SI may provide a broader, more accurate, representation of changes in movement in response to COVID-19.

1. Introduction

COVID-19 is a highly infectious viral infection [1]. As drug based medicinal treatments and vaccines were lacking as the epidemic gathered pace, reducing social interaction and limiting movement was seen as key in reducing viral transmission rates [2,3]. Governments globally were swift in imposing legal restrictions banning public gatherings and sports events, closing schools, and restricting movement in order to halt transmission [4]. Initial evidence from China suggested such measures could effectively limit viral spread [5–7].

The response of the Swedish government to the COVID-19 pandemic of the spring of 2020 contrasted noticeably to that of both its Scandianvian and European neighbours. Sweden imposed few legal restrictions, instead relying on compliance with government advice and recommendation [8]. This strategy attracted much media attention [9, 10]. The restrictions imposed by other neighbouring Scandinavian countries were much stricter.

Are the differences in the severity of restrictions, and subsequent mobility, reflected in later mortality data? The excess mortality from COVID-19 for Sweden during the first wave of the pandemic was one of the highest in the world, greatly exceeding that seen in its Scandinavian neighbours [11]. This is despite socio-economic and cultural features being similar across these countries, as shown by key statistics (Population 2019; Denmark, 5,806,081; Finland, 5,517,919; Sweden, 10, 230, 185; Norway, 5,367,580), (GDP 2019; Denmark, 171.3; Finland, 140.1; Norway, 216.6; Sweden, 148.3) (Life expectancy 2018; Denmark, 82.9; Finland, 84.5; Norway, 84.5; Sweden, 84.5) [12].

Throughout the COVID-19 pandemic new sources of data which reflect both the governmental response to its spread, and the influence of the disease on the everyday lives of national inhabitants, have become available. The Oxford COVID-19 Government Response Tracker assesses the stringency of measures imposed by governments in response to COVID-19 worldwide providing a single indexed value, reflecting the overall severity of restrictions in any one nation on any one date [13].

This 'Stringency Index' (SI) gave Sweden an overall value of 35.19 at the end of March. In comparison, that of Denmark was 72.22, for Norway it was 79.63, and for Finland 60.19.

Google's 'Community Movement Records' (CMR) [14] are gathered from those accessing Google applications on mobile and hand-held electronic devices; they reflect the level of activity at key location types. They thus allow examination and comparison of mobility differences between countries. This novel source of data allows the trends in mobility which occurred in response to the measures imposed to hinder COVID-19 transmission to be studied and their possible impact on mortality to be examined.

Here, the relationship between these datasets; SI and CMR, and the number of COVID-19 related deaths was examined for Scandinavian countries. The association with mortality data was studied using cross-correlation analyses, effectively time shifting mortality data backwards, thus revealing the delayed influence restrictions had. Generalized Additive Modeling allows examination of non-linear datasets and can be used to compare the influence of separate variables on specific outcomes [15]. This was performed to examine whether CMR or SI was most effective in modeling the number of deaths across Scandinavia and to seek cross country-differences.

2. Materials and methods

2.1. Data

Google's CMR show the percentage change in activity at different location categories by those accessing Google applications on mobile devices, allowing recording of 'location history' [16]. Google provides data on six categories of locations; 'retail and recreation', 'grocery and pharmacy', 'parks', transport 'transit' hubs, 'workplace' or 'residential'. The median value of activity at each location, for each activity category, for each week day was ascertained over the period January 3, 2020 to February 6, 2020. This value was accorded as a baseline value of '100′ against which later activity was compared. Data is provided on a daily basis, and given as the percentage change in activity compared to baseline figures for the same week day. Full technical details are available [17]. Data was collated for Denmark, Finland, Norway, and Sweden from February 15, 2020 until October 10, 2020.

The Oxford COVID-19 Government Response Tracker [13] assesses the extent and severity of mobility restrictions imposed by countries in response to COVID-19 throughout the pandemic. These are collated into an overall index for each country throughout the period of the COVID-19 epidemic. This 'Stringency Index' (SI) is a widely used measure of movement restriction severity, and was downloaded for the time frame corresponding to CMR data.

Data on the daily number of recorded deaths attributed to COVID-19 in each country was obtained from the John Hopkins COVID-19 data repository, situated upon GitHub [18]. Each country's population size was obtained on October 25, 2020 [19].

2.2. Correlations

Datasets were split into a training (from 15 February to August 01, 2020) and validation dataset (from 02 August to October 10, 2020). This date was chosen as the cutoff, as being approximately the end of the 'first wave' of the epidemic; the number of deaths had peaked and were declining in each country.

The relationship between each mobility category and daily death number per million inhabitants was examined using a contemporaneous Spearman rank cross correlation from 15 February to October 10, 2020. To assess the potential delayed influence of mobility on COVID-19 cases, cross-correlation Spearman rank correlation analyses were performed where mortality figures were time shifted against mobility data with $\pm$ 28 days. To account for multiple testing, Holm correction was performed.

2.3. Modeling

Generalized Additive Modeling was performed using training data, with an initial model using the single variable of smoothed numerical date and the country as explanatory variable and daily death number per million of population as the response. Secondly, modeling using the smoothed country SI as well as date as explanatory variables was performed. The next, third, model used CMR mobility data, as well as date, as smoothed variables. Finally, a Distributed Lag Model with CMR mobility and SI data using $\pm$ 28 days lag was established; this effectively examines the potential delayed influence mobility had on deaths by using splines to describe the lagged effects. CMR mobility data for 'parks' was not used in modeling, due to the strong seasonal changes in activity anticipated for this category. Also, data on 'residential' activity was not used; this category is not indicative of levels of mobility. Models were compared on the basis of the Akaike Information Criterion (AIC).

Model validation was performed by making predictions of daily death numbers over the validation time frame, then comparing with actual reported deaths and the calculated root mean squared errors (RMSE) values. All calculations were performed using R 4.0.2 with mgcv and dlnm packages. The statistical code and all output and data files are available under the link: https://github.com/msulyok/COVIDMobilityScandinavia.

3. Results

3.1. Trends in CMR and SI

Fig. 1 shows trends in CMR throughout the period of study for each country. There are clear reductions in four of these categories, 'retail', 'grocery', 'transit' and 'workplace' across the countries examined at the beginning of March, followed by steady increases back to, and above, baselines figures by July. The exceptions are for 'park' and 'residential' activity. 'Park' activity increased steadily throughout the period. 'Residential' activity initially rose before steadily falling. Activity at 'residential' and 'park' locations would be expected to increase with increased 'stay at home' tendencies, and in the spring months when outdoor recreation becomes possible. Trends in Swedish mobility are comparable to those of its neighbours as can be seen in S1.

The reductions in mobility observed in the Spring of 2020 coincide both with the establishment of COVID-19 epidemics in each country and the imposition of government restrictions on social interaction and movement (Fig. 2). Denmark began to impose restrictions from the 3 March; Finland on the 12 and 16 March; Norway between the 10 and 12 March and again on the 24 March, and Sweden from the 12 March [13]. Index cases of COVID-19 were reported by Denmark on the 27 February and by Norway on the February 26, 2020) [20]. Sweden reported its first case on January 24, 2020, but the beginning of a sustained endemic epidemic began from 26 February [20]. Similarly, Finland's first reported case was on 29 January, but endemic cases were reported from 26 February onwards.

3.2. Correlations

Results of correlations between each mobility category and deaths are provided in Fig. 3. As expected, negative correlations are apparent using contemporaneous data for each country for those categories indicative of movement. Essentially, mobility declined as reported COVID-19 cases, and later deaths, gathered pace. Counterintuitively, a positive correlation is seen between SI and number of deaths. As restrictions were imposed and tightened, the numbers of deaths appeared to increase; however the lengthy delay which occurs between infection and ultimate death accounts for this apparent contradiction.

Examination of cross-correlation (Fig. 3) indicates similar patterns across countries. As deaths are shifted backwards in time, correlations become increasingly negative. Then with increasing lag times, the
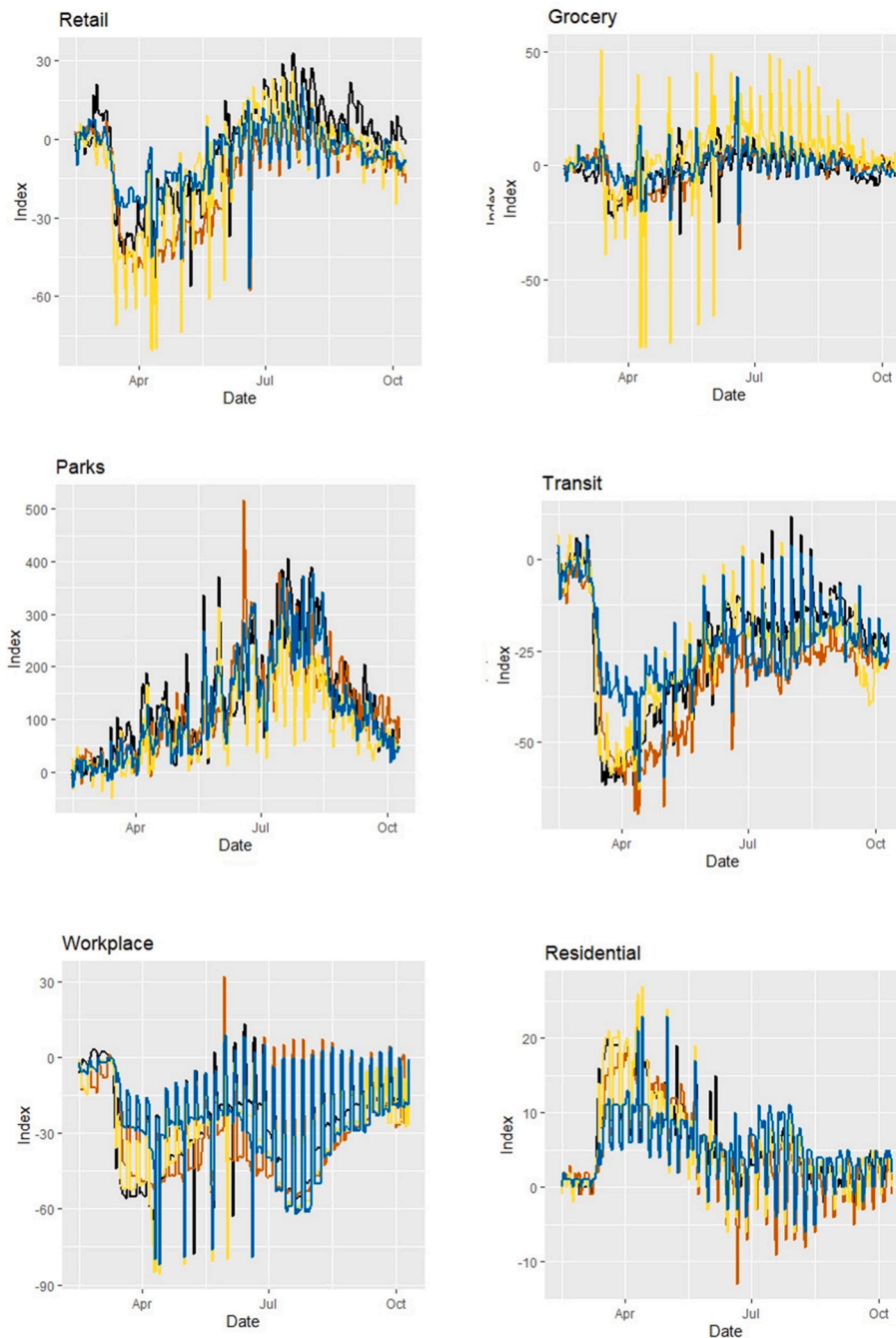
Fig. 1. Trends in Google's CMR from March to October 2020 for Denmark (Black), Finland (Red), Norway (Yellow) and Sweden (Blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

strength of negative correlation weakens. This may reflect the delay before the influence of mobility restrictions becomes apparent on death numbers.

Not unexpectedly, different patterns are observed for 'park' and 'residential' activity. For 'residential' a positive relationship is observed throughout. These patterns are observed across countries, with those for Sweden not being noticeably different than for the other three countries examined.

However, distinct cross country differences can be seen for the cross-correlations for SI. For Denmark, Finland and Norway a positive relationship was observed, with the strongest correlations occurring with small lags of −1 to −8 days. Sweden is a notable exception; the correlation being particularly strong (ρ 0.93), and with a +12 day lead. This

may reflect that Sweden imposed restrictions in response to rising death numbers, while the other countries anticipated rising death numbers and imposed restrictions before they occurred (see Table 1).

3.3. Modeling

Model comparison indicated that the model utilising SI was favorable to those using 'date' and 'country' alone, or with the addition of CMR data. Table 2 contrasts key model parameters. GAM model co-efficients are provided as supplementary material (S4). The AIC of the initial model using only 'date' and country was 961.46; 'date' was a significant smoothed variable for all countries, as was 'country' (with Sweden having a positive independent effect size on the death counts.
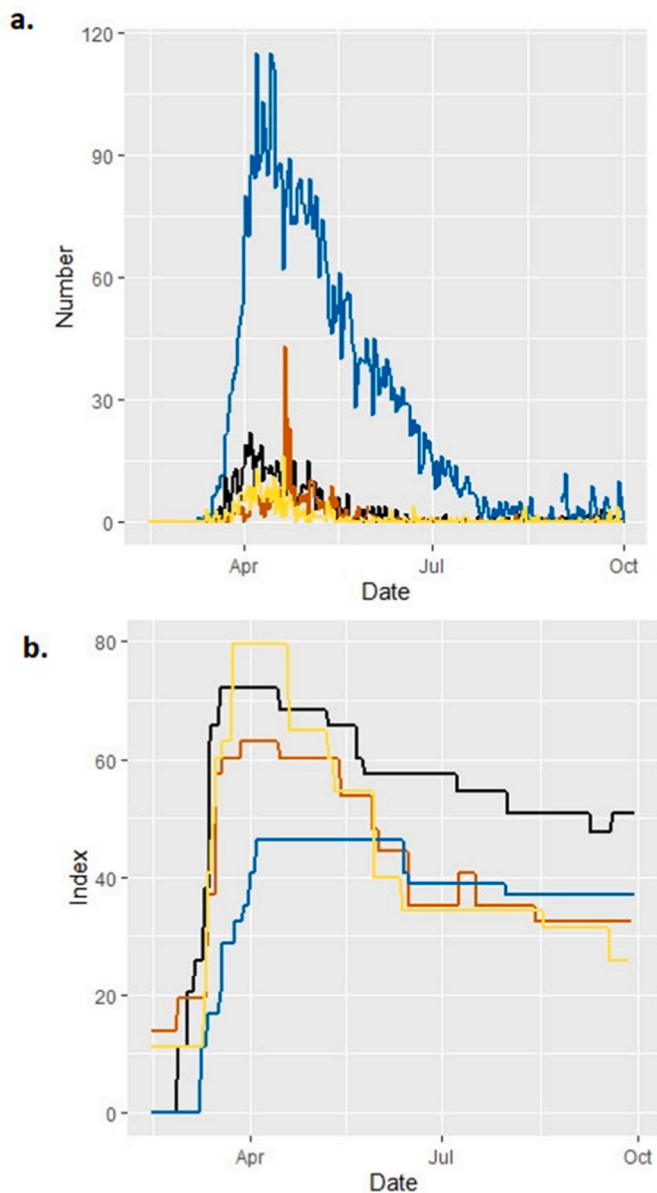
Fig. 2. (a) Daily number of deaths per million attributed to COVID-19 Data obtained from John Hopkins COVID-19 data repository [18]. **(b)** Stringency Index values for each country March to October 2020 [13]. Denmark (Black); Finland, (Red), Norway, (Yellow); Sweden, (Blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Integration of the SI, in Model 2, enhanced model quality to AIC 632.87. Whilst adding the contemporaneous smoothed CMR data, in Model 3, increased the AIC to 1193.84. The final, fourth model which used distributed Lag values for CMR and SI achieved the second best quality (AIC 642.35).

3.4. Model validation

Validating the models showed a similar hierarchy. The best RMSE (0.249) was achieved by the model using the smoothed date, country and SI, followed by the initial model without SI (RMSE 0.25), followed by the CMR expanded model (RMSE 0.522). The worst performing model was detected by the distributed lag model (RMSE 104.62), most errors coming from an overestimation in the number of deaths for Norway. Detailed model characteristics and residual diagnostics are

provided in the supplementary material (S4) and under the link: htt ps://github.com/msulyok/COVIDMobilityScandinavia.

3.5. Country differences

Importantly, when examining the influence of different countries in modelling, the country category of Sweden had a significant positive independent effect on the daily death counts across all models In other words, in modelling Swedish mortality numbers were significantly higher than those observed for the other three Scandinavian countries independently from SI and CMR data.

4. Discussion

4.1. Trends in CMR and SI

The Stringency Index for each Scandinavian country shows the increasing severity of restrictions imposed upon community social activity and movement during the initial phases of the COVID-19 epidemic. Corresponding declines in the CMR categories indicative of mobility are apparent across the Scandinavian countries examined, indicating the clear impact the COVID-19 epidemic and these restrictions had on movement. Although the extent of restrictions imposed in Sweden were notably less severe than in its neighbours, the reductions in mobility in Sweden were of a similar magnitude to those seen in its near neighbours. Moreover, the significant effect of the country category Sweden in the models including SI and CMR indicates that other hidden factors specific to Sweden could be accounting for the increased mortality seen in this country.

4.2. Correlations

CMR mobility categories were negatively correlated with COVID-19 mortality. The strongest correlations were obtained by negatively time lagging mortality data. The results of the cross-correlation exercise indicates that mobility restrictions possibly had a delayed influence on mortality figures. SI was positively correlated with death numbers.

4.3. Modeling

Comparison of different models found that a model using solely SI with smoothed numerical date and country category explained mortality figures more accurately than one's using either contemporaneous, or time lagged CMR and SI data. Models using CMR data were not favorable to those using only date and country alone.

There are a number of reasons SI data may result in better performing models than CMR data. Although CMR measures activity at important locations indicative of general community mobility, such as transit stations and workplaces, it remains nevertheless arguably a rather crude measure of mobility. The demographic of those using Google technology may not truly reflect the overall population, being likely to be younger, more wealthy, and with different lifestyle patterns [21]. COVID-19 mortality, however, occurs disproportionately in elderly age ranges [22]; those whose habits and levels of mobility may not be fully reflected in CMR data. By comparison, the SI values are collated using a broad range of social measures, including school closure and social gathering restrictions. Although some of these may not be direct measures of mobility, such as school closure, they are nonetheless important in determining overall levels of community mobility [23]. This may mean SI data better reflects actual levels of community mobility than CMR data. As SI represents the severity of government restrictions, this value is likely to better reflect true community activity in societies where adherence to such government restrictions is high, as is the case in Scandinavia [24]. The utility of SI in other countries, where such adherence is not as strong, would be of great interest.
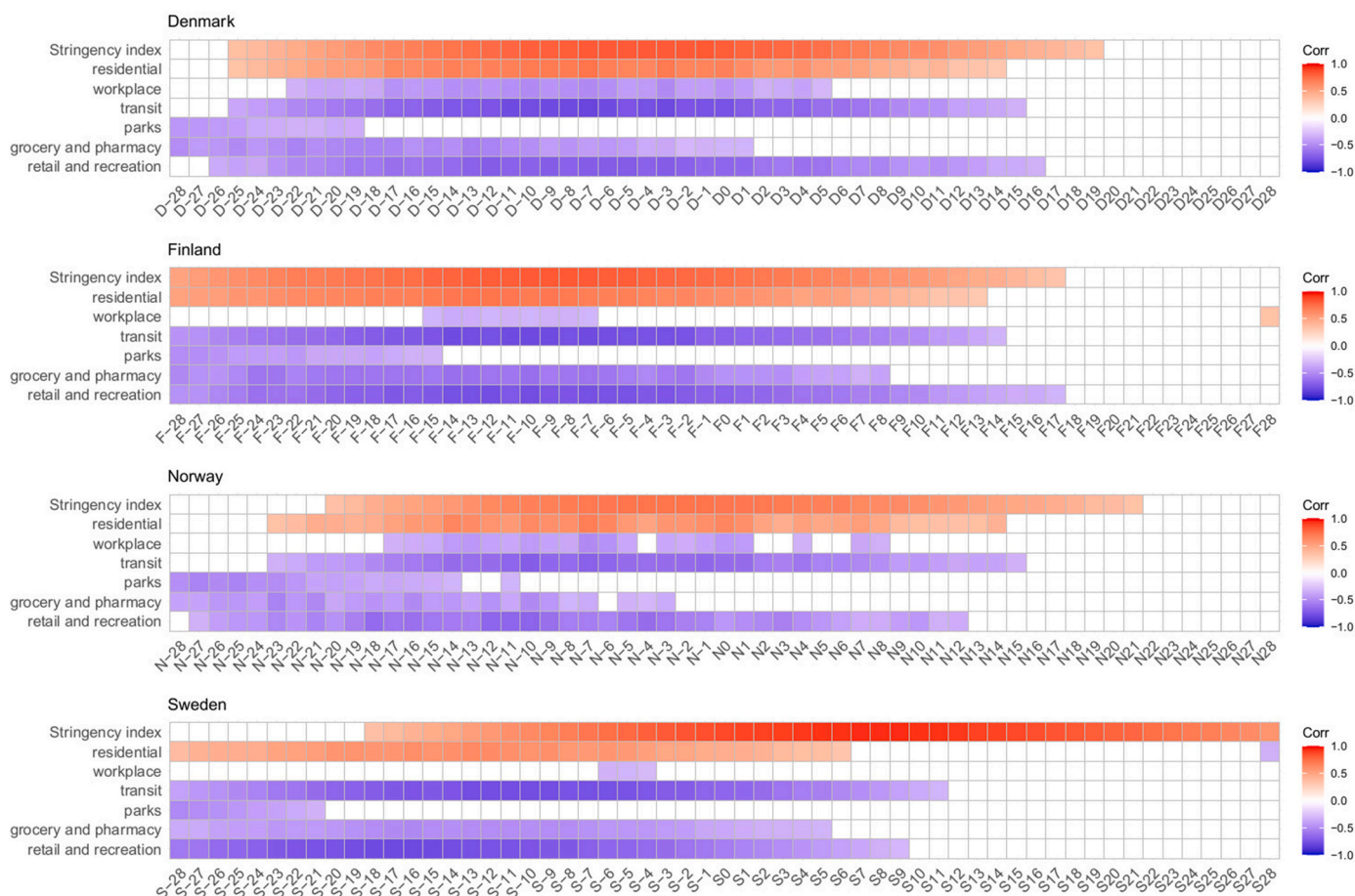
Fig. 3. Results of Spearman rank cross-correlations between CMR categories and SI and COVID-19 deaths between 15 February and October 10, 2020.

Table 1
Results of Spearman rank cross-correlation between mobility categories and country COVID-19 deaths between 15 February and 10 October. Maximum correlation values and time lag/lead. Values are ρ (number of day lags), all showed correlations were significant after multiple testing correction.

Crosscorrelations	Denmark	Finland	Norway	Sweden
'Retail'	−0.66 (−3)	−0.71 (−10)	−0.61 (-12)	−0.67 (−18)
'Grocery'	−0.49 (−22)	−0.58 (−16)	−0.47 (−23)	−0.34 (−26)
'Parks'	−0.52 (−27)	−0.56 (−28)	−0.55 (−25)	−0.71 (-28)
'Transit'	−0.73 (−7)	−0.72 (−11)	−0.60 (−7)	−0.72 (−7)
'Workplace'	−0.46 (−3)	−0.32 (−7)	−0.47 (−7)	−0.29 (0)
'Residential'	0.65 (−7)	0.69 (−13)	0.63 (−7)	0.61 (−6)
Stringency Index	0.71 (−1)	0.73 (−8)	0.63 (−2)	0.93 (12)

Table 2
Key model parameters; Model 1: 'date' and 'country' only, Model 2: with integration of Stringency index. Model 3: with integration of CMR data. Model 4: lag distributed model with CMR and Stringency Index.

Model	Variables	Adj. R^2	AIC	RSME (with validation dataset)
1	Date and Country	0.948	961.46	0.250
2	As Model 1, plus Stringency Index	0.95	632.87	0.249
3	As Model 2 plus, CMR data	0.96	1193.84	0.521
4	As Model 1 plus distributed lag CMR and SI data	0.946	642.35	104.62

4.4. Model validation

Validation confirmed that the model using SI without CMR data was favorable to those using CMR data. However models showed the potential value of both CMR and SI data in modeling future development of the epidemic. With refinement such data could be invaluable in modeling further waves of the pandemic for other countries, and in other contexts.

4.5. Country differences

Importantly a clear difference was apparent when examining the influence of each individual country in modeling. In contrast to other countries, Sweden proved unfavourable in modeling. Mortality rates were notably greater for Sweden, the influence of which is apparent in the initial model using only 'date' and 'country' (Fig. 4). However, a difference between Sweden and the other Scandianvian countries was also apparent even after CMR data, CMR and SI, or SI alone was used in modelling. In the SI based model this could possibly be expected as the severity of restrictions in Sweden were obviously less stringent than in its neighbours. However, CMR reductions were of a similar magnitude across countries, meaning the differences observed when modeling using this data are maybe more surprising.

It may be that country specific differences in mobility may be more subtle than is apparent in the broad categories provided in CMR data. The significant effect of the country category Sweden in models including SI alone, or with CMR, indicates that other hidden factors specific to Sweden could be accounting for the increased mortality. These factors are possibly not reflected in CMR or SI data.

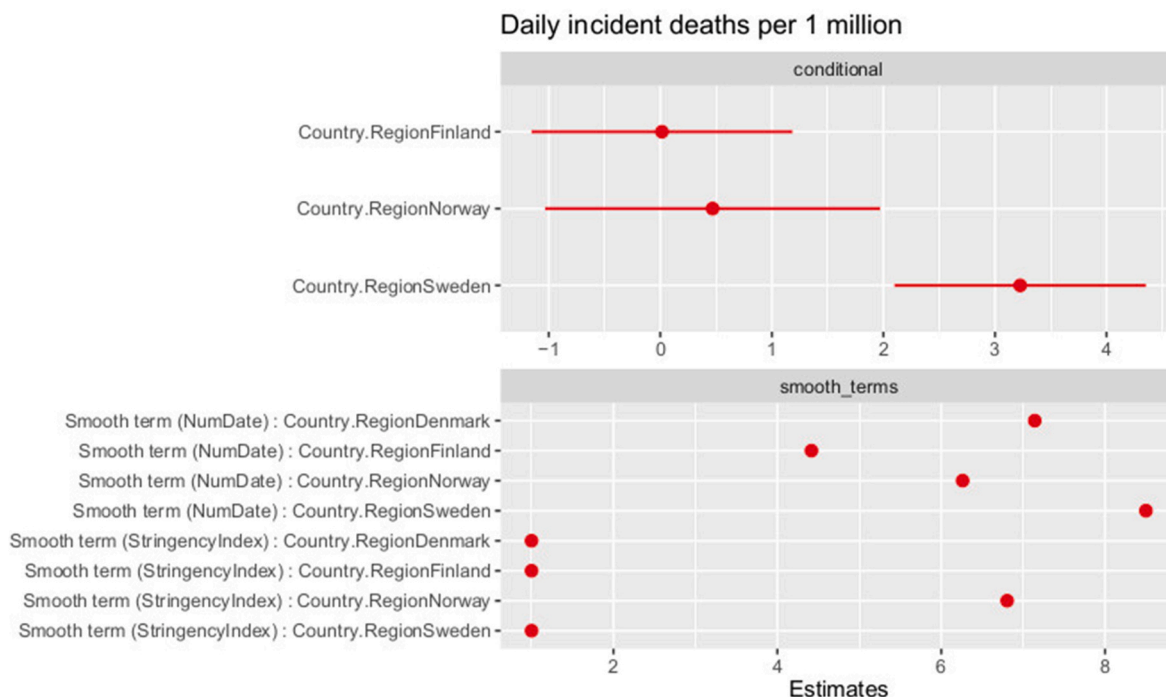Country specific population structure and socio-economic factors are

Fig. 4. Estimates and 95% confidence intervals of the best performing model using smoothed numerical date and country category as covariate with smoothed SI.

also likely to be of importance in disease transmission rates [25]; perhaps accounting for the difference observed in model performance between Sweden and its neighbours as observed here. Older populations may be more sedentary and cautious, those more wealthy may be in a better position financially to heed official advice. The Swedish population is highly educated and levels of social responsibility high which may account for the apparently high compliance with government requests to limit movement. A recent study has identified socio-economic factors as of possible importance in accounting for the elevated levels of mortality from COVID-19 in Sweden [26]. This study found a greater risk of mortailty in those in lower socio-economic groups and experiencing deprivation. Although results of surveying suggest those in at risk groups are complying with recommendations [24], those in disadvantaged economic situations may not be able to be as compliant. As already mentioned, comparison with countries where there are lower levels of confidence and trust in government advice would be interesting.

4.6. Mobility and COVID-19

The high transmissibility of COVID-19 means there has been much interest in studying the interaction between mobility and subsequent COVID-19 incidence [22]. It is intutive that the transmission of infectious diseases will be promoted by the free movement, and social interaction, of people. International travel is an easy avenue for investigation. A number of studies have shown that international travel restrictions have been shown to influence transmission and spread of COVID-19 [26,27]. Modeling suggests that internal travel restrictions in China, resulted in a delay of some days of exportation of the virus outside of China [28]. An early COVID-19 study suggested that social controls were effective at reducing transmission rates [6].

The effect of mobility on COVID-19 transmission within countries, and amongst communities, is more difficult to study. A number of studies have described the rapid spread of COVID-19 geographically; for example one study reported the spread of infection from the Chinese city of Suzhou, across 13 other cities within five days [29]. This study speculated that other factors such as population density may be important in facilitating infection spread.

A number of studies have used Google's CMR data to examine

aspects of COVID-19 transmission. A study of Google CMR across countries wordwide found an association between reductions in mobility reductions and subsequent COVID transmission [30]. A correlation between CMR data and U.S. county case numbers, using a +11 day lag, has been found [31]. Modeling using Google's CMR data showed that mobility reductions could reduce the size of the final pandemic and the timing of its peak [32]. The only other study we know that examined both a severity index and Google CMR compared these features across for South American countries [33].

4.7. General discussion

The success of the strategy employed by Sweden has been a subject of debate. Mortality rates have been considerably greater in Sweden than in its neighbours, even accounting for differences in population size, and there is speculation that this is due to the Swedish approach [34]. Analyses of the effect of stringency measures of differing severities are contradictory, some suggesting that harsher measures reduced mortality levels [35,36], but others finding that non-intervention was as effective as formal legislation would have been [8]. One study used synthetic control modeling to assess the impact non phamraceutical interventions would have had in Sweden if imposed to the same extent as in other countries [37]. This study speculated that the same restrictions in Sweden could have reduced cases by 75%, the effects of restrictions being apparent after five weeks.

Our results suggest that higher stringency is associated with lower death counts, and this effect appears to be more important than mobility. This may reflect the potential importance of government restrictions other than those restraining mobility, such as the use of public information campaigns or mandated mask wearing. Sweden proved to be significantly unfavourable factor across models, even in the best performing model utilising SI; this suggests the role of other possibly hidden factors not encompassed by the SI or CMR data. For instance, unmarried elderly people have been identified as being particularly at risk of death from COVID-19 in Sweden [38]. Thus an important factor could be the admittedly poor performance in protecting this most vulnerable group, often reliant on home help or in care homes. However, the more relaxed stringency measures were also associated with the

higher death counts independently. Other factors may be important in determining risk of mortality, with [32] for example citing population density as a possibly mitigating factor.

4.8. Limitations

There are limitations to CMR data. As mentioned it is only a crude measure of levels of social interaction. Activity levels are compared to baseline figures from January and February 2020. As Google acknowledge, this is only a short timeframe from which to produce baseline figures [39]. It is uncertain as to whether these baseline figures are a true reflection of mobility. Unexpected events may have influenced baseleine figures. Exmination of the influence of seasonal effects on baseline fitures would be of interest. It also provides no indication of adherence to, or the effect of, other disease mitigation strategies including social distancing, enhanced personal hygiene, or mask wearing. Another limitation is that the categories data is provided for is arbitary. Data on a different range of categories, such as to healthcare providers, would be of interest. More exact defining of categories would be desirable. A limitation of SI data is that although it reflects the severity of formal legislation on movement, such legal measures are not the only factors influencing personal movement decisions during this period. Personal motivations, including the perceived personal level of risk from infectious disease, are also important [40]. Media coverage relating to COVID-19 may influence personal decisions.

The work presented here does not consider the influence of household transmission. There is good evidence that infection spreads rapidly and easily amongst those living within the same household [41]. The Google Mobility data also does not reflect the influence of international travel. Travel for work purposes may involve international and cross border movement. Such movement has been shown to facilitate disease spread [41]. This could be important in Scandinavia, where cross country links are well developed.

4.9. Avenues for further study

This research examined the relationship between social activity and restriction severity on COVID-19 mortality using only two information sources; Google CMR and the Oxford SI. Other measures indicative of social activity, mobility and indeed various other aspects of social and eonomic activty could be utilised in further research. For example measures of economic output [42], including retail sales [43], or local and national energy consumption [44], and the relationship with COVID-19 incidence and mortality could be studied. Initial studies indicate that declines in electricity consumption occurred in response to COVID-19 [45]; whether national levels of energy use could be related to COVID-19 would be of interest.

Although there was significant disruption to healthcare services during the pandemic, investigation of the number of outpatient, accident and emergency, and visitors to other healthcare services, and how they relate to local and national COVID-19 incidence would be of interest [46]. Such study may uncover national differences. Another potential data source where interesting patterns related to COVID-19 data may be obtained could be Google Trends. For example recent studies have found increased interest in fitness during the pandemic [47]. There has been much research on the impact of COVID-19 restrictions on levels of air pollution [48]. Resources such as Google Earth Engine [49] or the European Space Agency Sentinel satellite [50] could provide additional data sources of study. Such data offers the potential to examine the relationship between geographical and environmental factors including climate on disease transmission.

5. Conclusion

In conclusion, clear reductions in mobility were apparent across the Scandinavian countries examined. These reductions were similar in magnitude, despite the fact that the severity of restrictions imposed varied between countries. Modeling suggests that models based upon restriction severity, and utilising a Severity Index, were favorable to those using direct measures of activity. The superiority of such models was confirmed by subsequent validation during the initial phases of the 'second wave' of the COVID-pandemic. Mobility and restriction severity data was effective in modeling deaths across countries; the category' Sweden' being independently and significantly unfavourable across models.

CRediT authorship contribution statement

Mihály Sulyok: Conceptualization, Methodology, Formal analysis, Data curation, Writing – review & editing. **Mark David Walker:** Conceptualization, Writing – original draft, Writing – review & editing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tmaid.2021.102039.

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