9 Appendix/ Supplementary material for the paper: Causal analysis of Covid-19 spread in Germany

9.1 Results of causal analysis on federal level for all four combinations of thresholds for SyPI
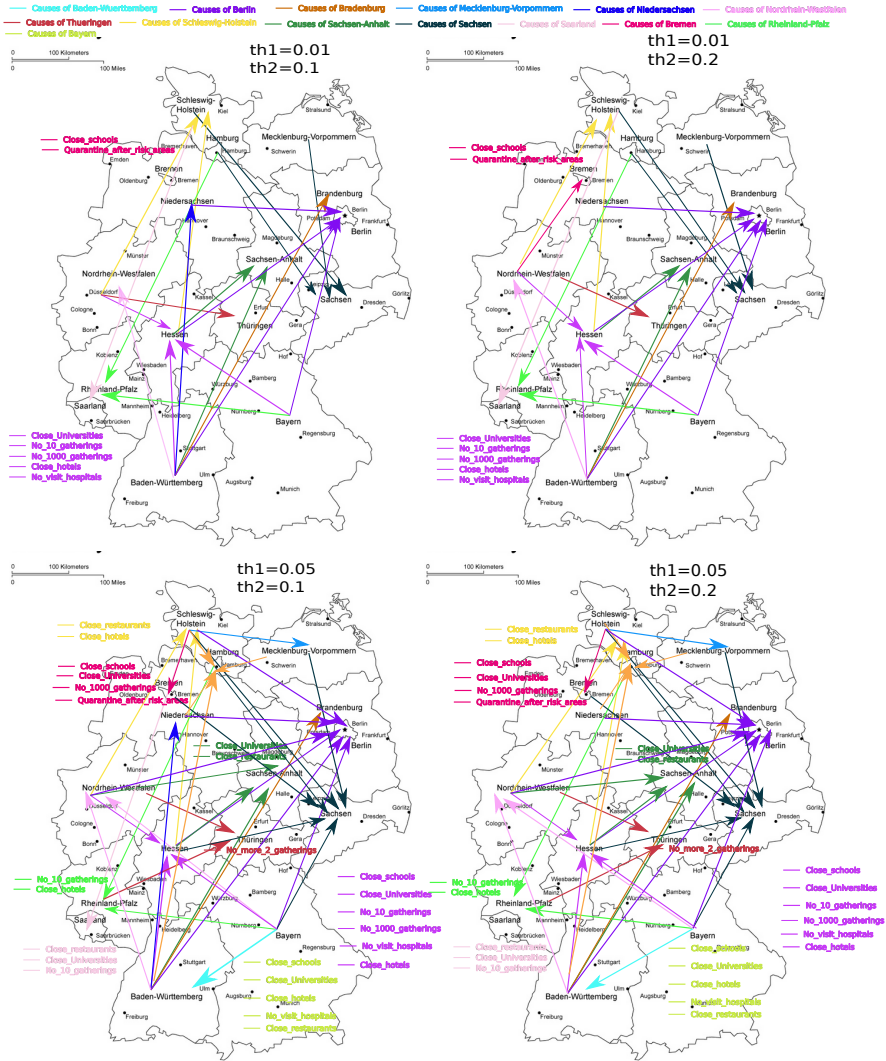

Figure 5: Detected causal paths of the spread of Covid-19 among the federal German states, including causes among the restriction measures taken by each federal state. Each colour (in arrows and policies) indicates causes of one state (see top legend). The four subfigures correspond to the four combinations of threshold 1 and 2 that we tested.

9.2 Theory

9.2.1 Definitions

Definition (Causal Faithfulness). *A distribution P is faithful to a directed acyclic graph (DAG) G if no conditional independence relations other than the ones entailed by the Markov property are present.*

Definition (Causal Markov Condition [16]). *Let G be a causal graph with vertex set $\mathcal{V}$ and P be a probability distribution over the vertices in V generated by the causal structure represented by G. G and P satisfy the Causal Markov Condition if and only if for every W in $\mathcal{V}$, W is independent of $\mathcal{V} \setminus (Descendants(W) \cup Parents(W))$ given $Parents(W)$.*

Here we use the global version of the Markov condition, which reads: if $\mathcal{X} \perp\!\!\!\perp_G \mathcal{Y} \mid \mathcal{Z} \Rightarrow \mathcal{X} \perp\!\!\!\perp \mathcal{Y} \mid \mathcal{Z}$ for all disjoint vertex sets $\mathcal{X}, \mathcal{Y}, \mathcal{Z}$ (where $\perp\!\!\!\perp_G$ denotes d-separation, as defined above)

9.2.2 Proof of Theorem A

Proof. The proof of Theorem 1 in [6] applies without changes. Regarding Theorem 2 in [6]: Assume that the direct path $X_t^i \to Y_{t+w_i}$ exists and it is unconfounded. Then, condition 1 of Theorem 2 in [6] is true. Now assume that condition 2 of Theorem 2 in [6] does not hold. This would mean that the set $\{\boldsymbol{S^i}, X_t^i, Y_{t+w_i-1}\}$ does not d-separate X_{t-1}^i and Y_{t+w_i}. (Recall that a path p is said to be *d-separated* by a set of nodes in Z if and only if p contains a chain or a fork such that the middle node is in Z, or if p contains a collider such that neither the middle node nor any of its descendants are in the Z.) Hence, a violation of condition 2 would imply that (a) there is some middle node or descendant of a collider in $\{\boldsymbol{S^i}, X_t^i, Y_{t+w_i-1}\}$ and no non-collider node in this path belongs to this set, or (b) that there is a collider-free path between X_{t-1}^i and Y_{t+w_i} that does not contain any node in $\{\boldsymbol{S^i}, X_t^i, Y_{t+w_i-1}\}$.

(a) *There is some middle node or descendant of a collider in $\{\boldsymbol{S^i}, X_t^i, Y_{t+w_i-1}\}$ and no non-collider node in this path belongs to this set:* the proof given in [6] remains unaffected if all $\mathbf{DE}_Y^{\mathcal{G}} \notin \mathbf{X}$, because any collider D or descendent of collider between some X_t^j and Y_{t+w_i} will be unobserved, therefore will not be possible to belong in the conditioning set $\{\boldsymbol{S^i}, X_t^i, Y_{t+w_i-1}\}$.

(b) *There is a collider-free path between X_{t-1}^i and Y_{t+w_i} that does not contain any node in $\{\boldsymbol{S^i}, X_t^i, Y_{t+w_i-1}\}$:* the proof given in [6] remains unaffected.

$\square$

9.3 Simulation experiments

We applied SyPI with the modified assumption on simulated full time graphs, with varying numbers of observed time series and one hidden time series, for varying levels of noise. Dashed lines correspond to the missed direct causes false negative rate and the continuous lines to the false positive rate. We see that the result of the method remains unaffected by the relaxation of the assumption that we made. As expected from the proof of the theorem, FPR and FNR are not affected by the relaxation of the sink node assumption if $\mathbf{DE}_Y^{\mathcal{G}} \notin \mathbf{X}$.
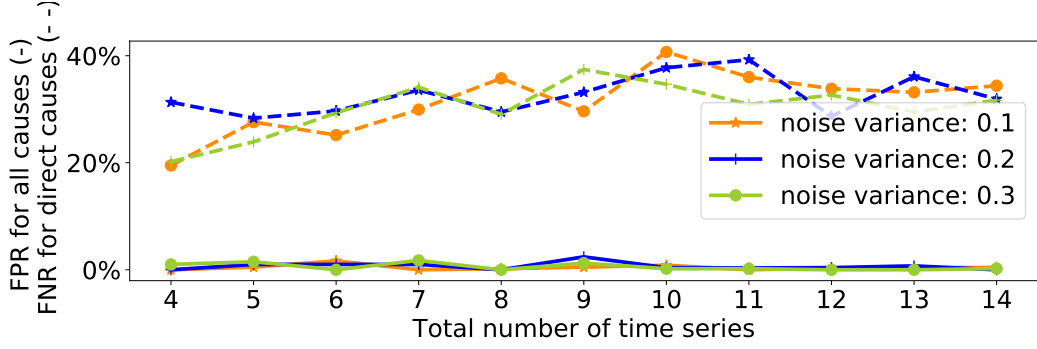
Figure 6: False positive and false negative rates for missed direct causes, in simulated graphs with varying number of observed time series and one hidden, for varying noise levels. Dashed lines correspond to the missed direct causes false negative rate and the continuous lines to the false positive rate. We see that the result of the method remains unaffected by the relaxation of the assumption that we made. As expected from the proof of the theorem, FPR and FNR are not affected by the relaxation of the sink node assumption if $\mathbf{DE}_Y^{\mathcal{G}} \notin \mathbf{X}$.

9.4 Detailed findings from comparison of modified SyPI with Lasso-Granger and tsFCI of the Covid-19 spread among the German federal states.
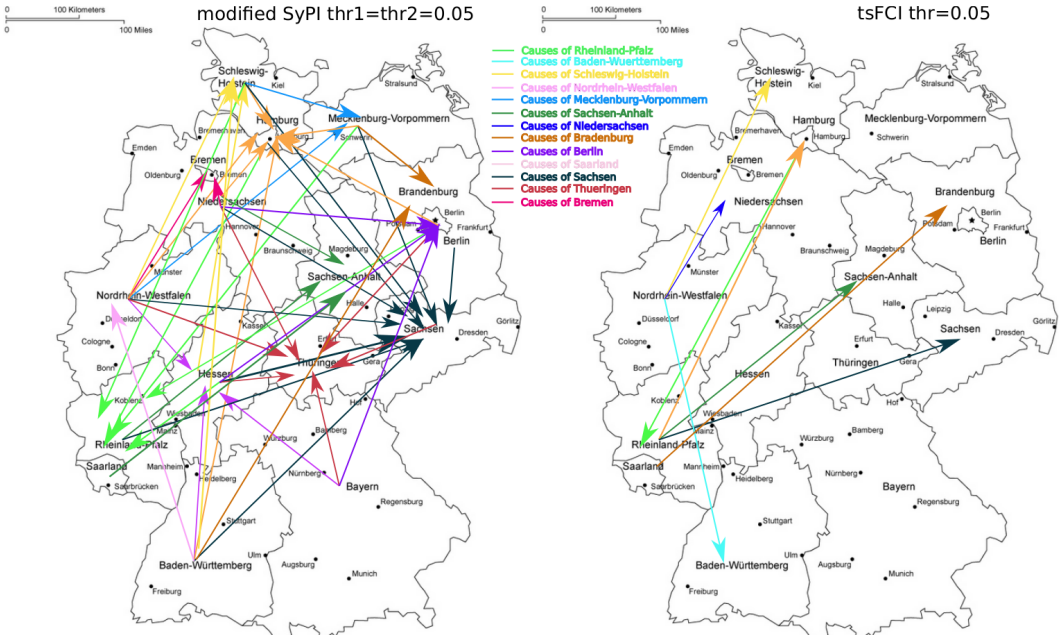

Figure 7: Detected causes for each federal state until 15/05/2020. Left: SyPI $(0.05, 0.05)$. Right: tsFCI (0.05). tsFCI detected eight, while SyPI 44 directed edges (causes). Four of the detected causes by tsFCI were a subset of the ones detected by SyPI. For the majority of the remaining states tsFCI yielded '↔', without being able to conclude to one direction.

Table 1: Detected causes for each federal German state (Bundesland), using SyPI with the loose combination of thresholds $(0.05, 0.1)$ (2nd column) and using Lasso-Granger (3rd column). As expected we see that the number of detected causes by Granger is multiple times more than those of SyPI; in most cases Granger detects as causes all the candidate states. Without knowing the ground truth, this is an obvious indication that the dataset includes hidden confounders, that make the federal states look all related to each other. This violation of causal sufficiency makes Granger to fail, as expected. On the other hand, SyPI does not suffer from such problems even when there are latent confounders.

Target	Predicted causes by SyPI	Predicted causes by Granger
Bayern	Close schools, Close universities, Close restaurants, Close hotels, Prohibit visits at hospitals	Close schools, Close universities, No more than 1000 people gatherings, No more than 10 people gatherings, Quarantine 14 days after visiting risk areas, No more than 2 people gatherings, Close restaurants, Close hotels, Prohibit visits at hospitals
Baden-Württemberg	Bayern	Bayern, Close schools, Close universities, No more than 1000 people gatherings, No more than 10 people gatherings, Quarantine 14 days after visiting risk areas, No more than 2 people gatherings, Close restaurants, Close hotels, Prohibit visits at hospitals
Nordrhein-Westfalen	Bayern, Baden-Württemberg	Bayern, Baden-Württemberg, Close schools, No more than 1000 people gatherings, No more than 10 people gatherings, Quarantine 14 days after visiting risk areas, No more than 2 people gatherings, Close restaurants, Close hotels, Prohibit visits at hospitals
Hessen	Bayern, Baden-Württemberg, Nordrhein-Westfalen, Close schools, Close universities, No more than 1000 people gatherings, No more than 10 people gatherings, Close hotels, Prohibit visits at hospitals	Bayern, Baden-Württemberg, Nordrhein-Westfalen, Close schools, Close universities, No more than 1000 people gatherings, No more than 10 people gatherings, Quarantine 14 days after visiting risk areas, No more than 2 people gatherings, Close restaurants, Close hotels, Prohibit visits at hospitals
Niedersachsen	Baden-Württemberg	Bayern, Baden-Württemberg, Nordrhein-Westfalen, Hessen
Schleswig-Holstein	Nordrhein-Westfalen, Hessen, Close restaurants, Close hotels	Bayern, Baden-Württemberg, Nordrhein-Westfalen, Hessen, Niedersachsen, Close schools, No more than 1000 people gatherings, No more than 2 people gatherings, Close restaurants, Close hotels, Prohibit visits at hospitals
Berlin	Bayern, Baden-Württemberg, Nordrhein-Westfalen, Hessen, Niedersachsen, Schleswig-Holstein	Bayern, Baden-Württemberg, Nordrhein-Westfalen, Hessen, Niedersachsen, Schleswig-Holstein, Close schools, No more than 10 people gatherings, Close restaurants, Close hotels, Prohibit visits at hospitals
Bremen	Schleswig-Holstein, Close schools, Close universities, No more than 1000 people gatherings, Quarantine 14 days after visiting risk areas	Bayern, Baden-Württemberg, Nordrhein-Westfalen, Hessen, Niedersachsen, Schleswig-Holstein, Berlin, Close schools, Close universities, No more than 1000 people gatherings, No more than 10 people gatherings, Quarantine 14 days after visiting risk areas, No more than 2 people gatherings, Close restaurants, Close hotels, Prohibit visits at hospitals
Mecklenburg-Vorpommern	Schleswig-Holstein	Bayern, Baden-Württemberg, Nordrhein-Westfalen, Hessen, Niedersachsen, Schleswig-Holstein, Berlin, Bremen, Close schools, Close universities, No more than 1000 people gatherings, No more than 10 people gatherings, Quarantine 14 days after visiting risk areas, Close restaurants, Close hotels, Prohibit visits at hospitals
Hamburg	Baden-Württemberg, Niedersachsen, Schleswig-Holstein, Mecklenburg-Vorpommern	Bayern, Baden-Württemberg, Nordrhein-Westfalen, Hessen, Niedersachsen, Schleswig-Holstein, Berlin, Bremen, Mecklenburg-Vorpommern, Close schools, Close universities, No more than 1000 people gatherings, No more than 10 people gatherings, Quarantine 14 days after visiting risk areas, Close restaurants, Close hotels, Prohibit visits at hospitals
Rheinland-Pfalz	Bayern, Hamburg, No more than 10 people gatherings, Close hotels	Bayern, Baden-Württemberg, Nordrhein-Westfalen, Hessen, Niedersachsen, Schleswig-Holstein, Berlin, Bremen, Mecklenburg-Vorpommern, Hamburg, Close schools, No more than 1000 people gatherings, No more than 10 people gatherings, Close restaurants, Close hotels, Prohibit visits at hospitals
Sachsen	Bayern, Hessen, Schleswig-Holstein, Bremen, Mecklenburg-Vorpommern, Hamburg	Bayern, Baden-Württemberg, Nordrhein-Westfalen, Hessen, Niedersachsen, Schleswig-Holstein, Berlin, Bremen, Mecklenburg-Vorpommern, Hamburg, Rheinland-Pfalz, Close schools, Close universities, No more than 1000 people gatherings, Close hotels, Prohibit visits at hospitals
Brandenburg	Baden-Württemberg	Bayern, Baden-Württemberg, Nordrhein-Westfalen, Hessen, Niedersachsen, Schleswig-Holstein, Berlin, Bremen, Mecklenburg-Vorpommern, Hamburg, Rheinland-Pfalz, Sachsen, Close schools, Close universities, No more than 1000 people gatherings, No more than 10 people gatherings, Close restaurants, Close hotels, Prohibit visits at hospitals
Saarland	Schleswig-Holstein, Close universities, No more than 10 people gatherings, Close restaurants	Bayern, Baden-Württemberg, Nordrhein-Westfalen, Hessen, Niedersachsen, Schleswig-Holstein, Berlin, Bremen, Mecklenburg-Vorpommern, Hamburg, Rheinland-Pfalz, Sachsen, Brandenburg, Close schools, Close universities, No more than 1000 people gatherings, No more than 10 people gatherings, Close restaurants, Close hotels, Prohibit visits at hospitals
Sachsen-Anhalt	Baden-Württemberg, Nordrhein-Westfalen, Hessen, Close universities, Close restaurants	Bayern, Baden-Württemberg, Nordrhein-Westfalen, Hessen, Niedersachsen, Schleswig-Holstein, Berlin, Bremen, Mecklenburg-Vorpommern, Hamburg, Rheinland-Pfalz, Sachsen, Brandenburg, Saarland, Close schools, Close universities, No more than 1000 people gatherings, Quarantine 14 days after visiting risk areas, Close restaurants, Close hotels, Prohibit visits at hospitals
Thüringen	Nordrhein-Westfalen, Rheinland-Pfalz, No more than 2 people gatherings	Bayern, Baden-Württemberg, Nordrhein-Westfalen, Hessen, Niedersachsen, Schleswig-Holstein, Berlin, Bremen, Mecklenburg-Vorpommern, Hamburg, Rheinland-Pfalz, Sachsen, Brandenburg, Saarland, Sachsen-Anhalt, Close schools, Close universities, No more than 1000 people gatherings, Quarantine 14 days after visiting risk areas, No more than 2 people gatherings, Close restaurants, Close hotels, Prohibit visits at hospitals

9.5 Detailed findings from the causal analysis of the Covid-19 spread among the German district states.

Table 2: Detected causes for each district German state, using SyPI. In the first column, the target district state is reported. In the second column, the detected causes among the neighbouring districts are reported. Finally, in the third column, we report the detected distant causes. Strict thresholds (the default of SyPI method) are used for the analysis. As explained in Section 4.3 and in Figure 4a, the majority of detected district causes are neighbours of the targets, and the majority of the distant detected causes are located close to a big airport.

Target distric state	Detected neighbouring causes	Detected distant causes
SK Gelsenkirchen	[]	[]
LK Landsberg a.Lech	[]	[]
LK Starnberg	[]	[]
LK Fürstenfeldbruck	[]	SK Gelsenkirchen
SK München	[]	[]
LK Traunstein	[]	[]
SK Delmenhorst	[]	[]
LK München	LK Starnberg	[]
LK Freising	LK München	[]
SK Köln	[]	[]
LK Lippe	[]	[]
LK Stormarn	[]	[]
LK Ravensburg	[]	[]
LK Göppingen	[]	[]
LK Tübingen	[]	[]
SK Freiburg i.Breisgau	[]	[]
LK Rottweil	[]	[]
LK Heinsberg	[]	[]
LK Breisgau-Hochschwarzwald	SK Freiburg i.Breisgau	[]
LK Böblingen	[]	LK München
SK Erlangen	[]	[]
LK Ludwigsburg	[]	SK Freiburg i.Breisgau
LK Viersen	[]	[]
StadtRegion Aachen	[]	[]
SK Kaiserslautern	[]	[]
LK Wesel	[]	[]
SK Hamburg	[]	[]
LK Märkischer Kreis	[]	[]
SK Fürth	[]	[]
LK Heilbronn	LK Ludwigsburg	[]
LK Ostalbkreis	[]	[]
LK Gießen	[]	[]
SK Bonn	[]	[]
LK Alb-Donau-Kreis	LK Göppingen	SK Fürth
LK Segeberg	[]	[]
LK Rhein-Neckar-Kreis	[]	LK Böblingen
SK Mönchengladbach	[]	[]
LK Ostallgäu	[]	[]
SK Lübeck	[]	[]
SK Schwabach	[]	[]
LK Lahn-Dill-Kreis	[]	[]
SK Bremen	[]	[]
SK Duisburg	[]	[]
LK Oberhavel	[]	[]
LK Düren	[]	[]
LK Groß-Gerau	[]	[]
SK Heilbronn	[]	[]
SK Münster	[]	[]
Region Hannover	[]	[]
LK Borken	[]	[]
SK Frankfurt am Main	[]	[]
LK Herzogtum Lauenburg	[]	[]
LK Hochtaunuskreis	[]	[]
LK Zollernalbkreis	LK Rottweil, LK Tübingen	[]
SK Nürnberg	SK Erlangen	LK Segeberg, SK Gelsenkirchen
LK Rheinisch-Bergischer Kreis	[]	[]
SK Mannheim	[]	[]
LK Rhein-Kreis Neuss	[]	[]
LK Sächsische Schweiz-Osterzgebirge	[]	[]
LK Ebersberg	LK München	[]
LK Cuxhaven	[]	[]
LK Rosenheim	LK Ebersberg, LK München	[]
SK Berlin Marzahn-Hellersdorf	[]	[]
SK Berlin Mitte	[]	[]
SK Berlin Neukölln	[]	[]
SK Ulm	[]	[]
LK Passau	[]	[]
LK Saale-Orla-Kreis	[]	[]
LK Lörrach	[]	[]
LK Rems-Murr-Kreis	LK Heilbronn, LK Ludwigsburg	LK Ebersberg, LK Wesel
LK Rhein-Sieg-Kreis	[]	[]
LK Main-Kinzig-Kreis	SK Frankfurt am Main	[]
LK Pinneberg	[]	[]
LK Esslingen	LK Rems-Murr-Kreis	[]
LK Bergstraße	[]	[]
LK Karlsruhe	[]	LK Freising
LK Oberbergischer Kreis	[]	[]
LK Ammerland	[]	[]

Target distric state	Detected neighbouring causes	Detected distant causes
LK Vorpommern-Greifswald	[]	[]
SK Bochum	[]	[]
SK Berlin Tempelhof-Schöneberg	[]	[]
LK Rotenburg (Wümme)	[]	[]
LK Mecklenburgische Seenplatte	[]	SK Berlin Tempelhof-Schöneberg
LK Main-Tauber-Kreis	[]	[]
LK Coesfeld	[]	[]
SK Düsseldorf	[]	[]
SK Berlin Pankow	[]	SK Nürnberg
SK Stuttgart	[]	[]
LK Emmendingen	LK Breisgau-Hochschwarzwald, SK Freiburg i.Breisgau	[]
SK Berlin Friedrichshain-Kreuzberg	SK Berlin Mitte, SK Berlin Tempelhof-Schöneberg	LK Starnberg
LK Sigmaringen	[]	[]
LK Grafschaft Bentheim	[]	[]
SK Mainz	[]	[]
SK Heidelberg	SK Mannheim	[]
LK Bad Dürkheim	[]	[]
LK Germersheim	[]	[]
LK Neckar-Odenwald-Kreis	LK Heilbronn	LK Breisgau-Hochschwarzwald
LK Cham	[]	[]
SK Koblenz	[]	[]
SK Oldenburg	[]	[]
LK Leer	[]	[]
LK Aichach-Friedberg	[]	[]
LK Vorpommern-Rügen	[]	LK Zollernalbkreis, SK Münster
LK Roth	[]	[]
LK Bodenseekreis	LK Ravensburg	[]
LK Osnabrück	[]	[]
LK Stade	[]	[]
LK Rhein-Erft-Kreis	[]	[]
LK Rheingau-Taunus-Kreis	LK Hochtaunuskreis	[]
LK Neu-Ulm	SK Ulm	[]
LK Unna	[]	[]
LK Weilheim-Schongau	LK Starnberg	LK Viersen
LK Waldeck-Frankenberg	[]	[]
LK Oberallgäu	LK Ravensburg, LK Ostallgäu	[]
LK Vogelsbergkreis	LK Gießen	LK Borken
LK Ortenaukreis	LK Emmendingen	[]
SK Berlin Reinickendorf	[]	[]
LK Miesbach	LK Rosenheim	LK Sigmaringen
SK Braunschweig	[]	[]
LK Dithmarschen	[]	[]
LK Hohenlohekreis	[]	[]
SK Dortmund	[]	[]
LK Calw	LK Karlsruhe	LK Ravensburg
LK Bad Kissingen	[]	[]
LK Euskirchen	[]	[]
LK Celle	Region Hannover	[]
SK Würzburg	[]	[]
LK Erlangen-Höchstadt	SK Erlangen	LK Ammerland, SK Berlin Mitte
LK Havelland	[]	LK Ludwigsburg
LK Konstanz	LK Sigmaringen	[]
SK Ingolstadt	[]	[]
LK Würzburg	[]	LK Erlangen-Höchstadt
SK Karlsruhe	LK Karlsruhe	LK Lahn-Dill-Kreis, LK Bodenseekreis
SK Kempten	[]	[]
SK Leipzig	[]	[]
SK Augsburg	[]	[]
LK Biberach	LK Neu-Ulm	[]
LK Minden-Lübbecke	[]	[]
LK Bautzen	[]	[]
LK Mettmann	[]	[]
LK Harburg	SK Hamburg	SK Erlangen, LK Gießen, LK Zollernalbkreis
SK Berlin Charlottenburg-Wilmersdorf	[]	[]
SK Bielefeld	[]	[]
LK Herford	[]	[]
LK Kassel	[]	[]
SK Essen	[]	[]
SK Rosenheim	LK Rosenheim	[]
SK Hof	[]	[]
LK Warendorf	[]	[]
SK Wilhelmshaven	[]	[]
LK Rastatt	[]	[]
LK Bitburg-Prüm	[]	[]
LK Fürth	[]	[]
LK Enzkreis	[]	SK Ingolstadt
SK Dresden	[]	[]
SK Baden-Baden	[]	[]
LK Ennepe-Ruhr-Kreis	[]	[]
LK Hildesheim	[]	[]
LK Offenbach	SK Frankfurt am Main	[]
LK Steinfurt	[]	[]
LK Schwarzwald-Baar-Kreis	LK Breisgau-Hochschwarzwald	SK Berlin Reinickendorf, LK Rhein-Neckar-Kreis
SK Erfurt	[]	[]
LK Freudenstadt	LK Tübingen	LK Oberallgäu
LK Regensburg	LK Cham	LK Segeberg
LK Tuttlingen	LK Schwarzwald-Baar-Kreis, LK Sigmaringen, LK Zollernalbkreis	LK Germersheim, SK Koblenz, LK Vogelsbergkreis

Target distric state	Detected neighbouring causes	Detected distant causes
LK Pfaffenhofen a.d.Ilm	LK Aichach-Friedberg, LK Freising	LK Bergstraße
LK Teltow-Fläming	SK Berlin Tempelhof-Schöneberg	[]
LK Schwandorf	LK Regensburg	LK Borken
LK Reutlingen	LK Esslingen	LK Lörrach, SK Freiburg i.Breisgau
LK Rostock	LK Vorpommern-Rügen	[]
LK Friesland	[]	LK Lörrach, LK Viersen
SK Aschaffenburg	[]	[]
SK Berlin Spandau	LK Havelland	LK Oberallgäu
LK Merzig-Wadern	[]	[]
LK Spree-Neiße	[]	[]
LK Saar-Pfalz-Kreis	[]	[]
SK Osnabrück	[]	[]
LK Schwäbisch Hall	LK Rems-Murr-Kreis	LK Ludwigsburg, SK Hof, SK Berlin Friedrichshain-Kreuzberg
LK Plön	[]	[]
LK Dingolfing-Landau	[]	[]
SK Offenbach	[]	[]
LK Dachau	[]	[]
LK Straubing-Bogen	[]	[]
LK Saarlouis	[]	[]
LK Stadtverband Saarbrücken	[]	[]
LK Rottal-Inn	[]	SK Berlin Charlottenburg-Wilmersdorf
SK Wiesbaden	[]	[]
SK Bottrop	[]	[]
LK Donau-Ries	LK Aichach-Friedberg	[]
LK Kelheim	LK Freising, LK Pfaffenhofen a.d.Ilm, LK Regensburg	LK Düren
LK Landshut	LK Dingolfing-Landau, LK Freising, LK Kelheim, LK Regensburg, LK Rottal-Inn	LK Vogelsbergkreis
SK Bremerhaven	[]	[]
LK Leipzig	[]	[]
SK Berlin Steglitz-Zehlendorf	[]	LK Stadtverband Saarbrücken, LK Pinneberg, LK Schwäbisch Hall
LK Lindau	LK Bodenseekreis	LK Kelheim
LK Main-Spessart	LK Bad Kissingen	SK Fürth, LK Lippe
LK Marburg-Biedenkopf	[]	[]
SK Berlin Lichtenberg	SK Berlin Marzahn-Hellersdorf	LK Fürth
SK Hagen	[]	[]
LK Görlitz	[]	[]
LK Garmisch-Partenkirchen	LK Ostallgäu, LK Weilheim-Schongau	SK Heidelberg
LK Fulda	LK Bad Kissingen	LK Sächsische Schweiz-Osterzgebirge
LK Neunkirchen	[]	[]
LK Mayen-Koblenz	[]	[]
LK Neuwied	[]	[]
LK Elbe-Elster	[]	[]
LK Emsland	LK Leer, LK Osnabrück, LK Steinfurt	[]
LK Oldenburg	[]	[]
LK Neustadt a.d.Aisch-Bad Windsheim	[]	LK Mayen-Koblenz
LK Erding	LK Freising, LK Landshut, LK München	[]
LK Oberspreewald-Lausitz	[]	[]
SK Pforzheim	[]	[]
SK Berlin Treptow-Köpenick	SK Berlin Friedrichshain-Kreuzberg	[]
SK Krefeld	[]	[]
LK Siegen-Wittgenstein	[]	[]
SK Kiel	[]	[]
LK Soest	[]	[]
LK Westerwaldkreis	[]	[]
SK Leverkusen	[]	[]
SK Chemnitz	[]	[]
SK Halle	[]	[]
SK Weimar	[]	[]
LK Waldshut	LK Breisgau-Hochschwarzwald	SK Nürnberg, LK Schwandorf
SK Weiden i.d.OPf.	[]	[]
LK Tirschenreuth	[]	[]
SK Solingen	[]	[]
SK Rostock	[]	[]
LK Vulkaneifel	[]	[]
SK Frankenthal	[]	[]
SK Magdeburg	[]	[]
SK Remscheid	[]	[]
LK Verden	[]	[]
SK Eisenach	[]	[]
LK Rhein-Hunsrück-Kreis	[]	[]
LK Paderborn	[]	[]
LK Burgenlandkreis	[]	[]
LK Märkisch-Oderland	[]	[]
LK Diepholz	[]	SK Braunschweig, LK Düren
LK Forchheim	[]	[]
LK Ostholstein	[]	[]
LK Osterholz	[]	[]
LK Oder-Spree	LK Märkisch-Oderland	[]
LK Hameln-Pyrmont	Region Hannover	SK Berlin Friedrichshain-Kreuzberg
LK Hochsauerlandkreis	[]	[]
LK Ilm-Kreis	[]	[]
LK Kitzingen	[]	[]
LK Kleve	[]	[]
LK Kyffhäuserkreis	[]	[]
LK Main-Taunus-Kreis	LK Hochtaunuskreis	[]
LK Meißen	[]	[]
LK Recklinghausen	[]	[]

Target distric state	Detected neighbouring causes	Detected distant causes
LK Bernkastel-Wittlich	[]	[]
LK Neumarkt i.d.OPf.	[]	LK Neustadt a.d.Aisch-Bad Windsheim
LK Bad Kreuznach	[]	[]
LK Saale-Holzland-Kreis	[]	[]
LK Aurich	[]	[]
LK Salzlandkreis	[]	[]
LK Amberg-Sulzbach	LK Schwandorf	[]
LK Saalekreis	[]	[]
LK Barnim	[]	[]
LK Bayreuth	LK Tirschenreuth	SK Augsburg
LK Mansfeld-Südharz	[]	[]
LK Lüneburg	[]	LK Konstanz
LK Anhalt-Bitterfeld	[]	[]
SK Straubing	[]	[]
LK Haßberge	[]	[]
SK Wuppertal	[]	[]
LK Kaiserslautern	[]	[]
SK Schwerin	[]	[]
LK Holzminden	LK Lippe	[]
LK Hof	LK Bayreuth	SK München
LK Aschaffenburg	[]	LK Neunkirchen
SK Emden	[]	[]
LK Mainz-Bingen	[]	[]
SK Neustadt a.d.Weinstraße	[]	[]
SK Gera	[]	[]
SK Oberhausen	[]	[]
LK Gifhorn	[]	[]
SK Herne	[]	[]
SK Salzgitter	[]	[]
LK Augsburg	[]	LK Saarlouis
SK Kassel	[]	[]
SK Kaufbeuren	LK Ostallgäu	[]
LK Bad Tölz-Wolfratshausen	LK Weilheim-Schongau	LK Bad Dürkheim, LK Landsberg a.Lech
LK Deggendorf	[]	[]
SK Ludwigshafen	[]	[]
LK Cloppenburg	LK Osnabrück	LK Rhein-Sieg-Kreis
LK Börde	[]	[]
LK Bamberg	LK Erlangen-Höchstadt, LK Forchheim	SK Berlin Reinickendorf
SK Mülheim a.d.Ruhr	[]	[]
LK Gütersloh	[]	[]
LK Schweinfurt	LK Bad Kissingen, LK Würzburg	SK Ulm
SK Cottbus	[]	[]
LK Rendsburg-Eckernförde	[]	[]
LK Northeim	[]	[]
LK Wittmund	[]	[]
LK Schleswig-Flensburg	[]	[]
LK Uelzen	[]	[]
LK Weißenburg-Gunzenhausen	LK Donau-Ries	[]
LK Nienburg (Weser)	[]	LK Passau
LK Unterallgäu	LK Augsburg, LK Oberallgäu	SK Köln
LK Olpe	[]	[]
LK Vechta	[]	[]
LK Rhein-Lahn-Kreis	[]	[]
LK Wetteraukreis	LK Hochtaunuskreis	[]
LK Regen	[]	LK Siegen-Wittgenstein
LK Cochem-Zell	[]	[]
LK Nordsachsen	[]	[]
LK Hersfeld-Rotenburg	LK Fulda, LK Vogelsbergkreis	LK Lahn-Dill-Kreis, LK Mettmann
LK Berchtesgadener Land	[]	[]
LK Potsdam-Mittelmark	[]	[]
LK Heidenheim	LK Emmendingen	[]
LK Ahrweiler	[]	[]
LK Darmstadt-Dieburg	[]	SK Köln
SK Landshut	[]	[]
LK Südliche Weinstraße	[]	[]
LK Nürnberger Land	LK Erlangen-Höchstadt	LK Würzburg, LK Minden-Lübbecke
LK Günzburg	LK Alb-Donau-Kreis	SK München
LK Göttingen	[]	SK Osnabrück
LK Donnersbergkreis	[]	[]
SK Hamm	[]	[]
LK Freyung-Grafenau	[]	[]
LK Dahme-Spreewald	[]	SK Ulm
LK Harz	[]	[]
LK Schwalm-Eder-Kreis	LK Marburg-Biedenkopf	[]
SK Passau	[]	[]
LK Schmalkalden-Meiningen	[]	[]
LK Altenkirchen	[]	[]
SK Bamberg	[]	[]
LK Altmarkkreis Salzwedel	[]	[]
LK Alzey-Worms	[]	[]
LK Miltenberg	LK Aschaffenburg, LK Main-Spessart	LK Bernkastel-Wittlich
SK Trier	[]	[]
LK Wittenberg	[]	[]
LK Eichstätt	LK Donau-Ries	LK Aschaffenburg
LK Sankt Wendel	[]	[]
LK Schaumburg	[]	[]
LK Kusel	[]	[]
LK Kulmbach	LK Hof	[]
LK Saalfeld-Rudolstadt	[]	[]
LK Nordfriesland	[]	[]

Target distric state	Detected neighbouring causes	Detected distant causes
LK Rhön-Grabfeld	LK Schmalkalden-Meiningen	[]
LK Rhein-Pfalz-Kreis	[]	[]
SK Regensburg	[]	[]
LK Zwickau	[]	[]
SK Suhl	[]	[]
LK Peine	[]	[]
SK Memmingen	LK Ravensburg	LK Esslingen, LK Emmendingen
LK Eichsfeld	[]	[]
LK Steinburg	[]	[]
SK Wolfsburg	[]	[]
LK Altenburger Land	[]	[]
SK Speyer	[]	[]
SK Amberg	[]	[]
LK Mittelsachsen	[]	[]
LK Heidekreis	LK Lüneburg, Region Hannover	SK Nürnberg, LK Heilbronn
SK Darmstadt	LK Darmstadt-Dieburg, LK Offenbach	[]
LK Erzgebirgskreis	[]	[]
LK Helmstedt	SK Braunschweig, SK Wolfsburg	[]
LK Nordhausen	[]	[]
LK Jerichower Land	[]	[]
LK Kronach	LK Kulmbach	LK Berchtesgadener Land
LK Lichtenfels	[]	LK Mittelsachsen
LK Limburg-Weilburg	[]	[]
LK Goslar	[]	[]
LK Ludwigslust-Parchim	[]	[]
LK Neustadt a.d.Waldnaab	LK Bayreuth, LK Tirschenreuth	[]
SK Worms	[]	[]
LK Höxter	[]	[]
LK Trier-Saarburg	[]	[]
LK Neuburg-Schrobenhausen	LK Donau-Ries	SK Frankfurt am Main
SK Jena	[]	[]
LK Coburg	[]	[]
LK Gotha	[]	[]
LK Greiz	[]	[]
LK Odenwaldkreis	[]	[]
LK Wartburgkreis	[]	[]
SK Flensburg	[]	[]
SK Landau i.d.Pfalz	[]	[]
LK Vogtlandkreis	[]	[]
LK Ansbach	LK Fürth, LK Roth	LK Dingolfing-Landau, SK Weiden i.d.OPf., LK Erzgebirgskreis
SK Ansbach	LK Ansbach	[]
SK Brandenburg a.d.Havel	LK Havelland	[]
LK Wunsiedel i.Fichtelgebirge	LK Tirschenreuth	SK Halle
LK Unstrut-Hainich-Kreis	[]	[]
LK Birkenfeld	[]	[]
LK Weimarer Land	[]	[]
LK Stendal	[]	[]
SK Dessau-Roßlau	[]	[]
LK Werra-Meißner-Kreis	LK Kassel, LK Schwalm-Eder-Kreis	[]
SK Coburg	[]	LK Hochsauerlandkreis
LK Nordwestmecklenburg	SK Schwerin	SK Rostock
LK Südwestpfalz	[]	[]
SK Neumünster	[]	[]
SK Potsdam	LK Havelland	SK Erlangen
LK Mühldorf a.Inn	LK Landshut, LK Traunstein	[]
SK Schweinfurt	[]	[]
SK Frankfurt (Oder)	[]	[]
LK Prignitz	[]	[]
LK Altötting	LK Rottal-Inn, LK Traunstein	SK Heidelberg, LK Hameln-Pyrmont
LK Wolfenbüttel	[]	[]
LK Uckermark	[]	LK Märkisch-Oderland, LK Rendsburg-Eckernförde
SK Bayreuth	[]	LK Neustadt a.d.Waldnaab
LK Ostprignitz-Ruppin	LK Oberhavel	[]
LK Wesermarsch	[]	[]
LK Dillingen a.d.Donau	[]	LK Märkischer Kreis
SK Pirmasens	[]	[]
LK Sömmerda	[]	[]
LK Lüchow-Dannenberg	[]	[]
LK Sonneberg	[]	[]
LK Hildburghausen	[]	[]
SK Zweibrücken	[]	[]

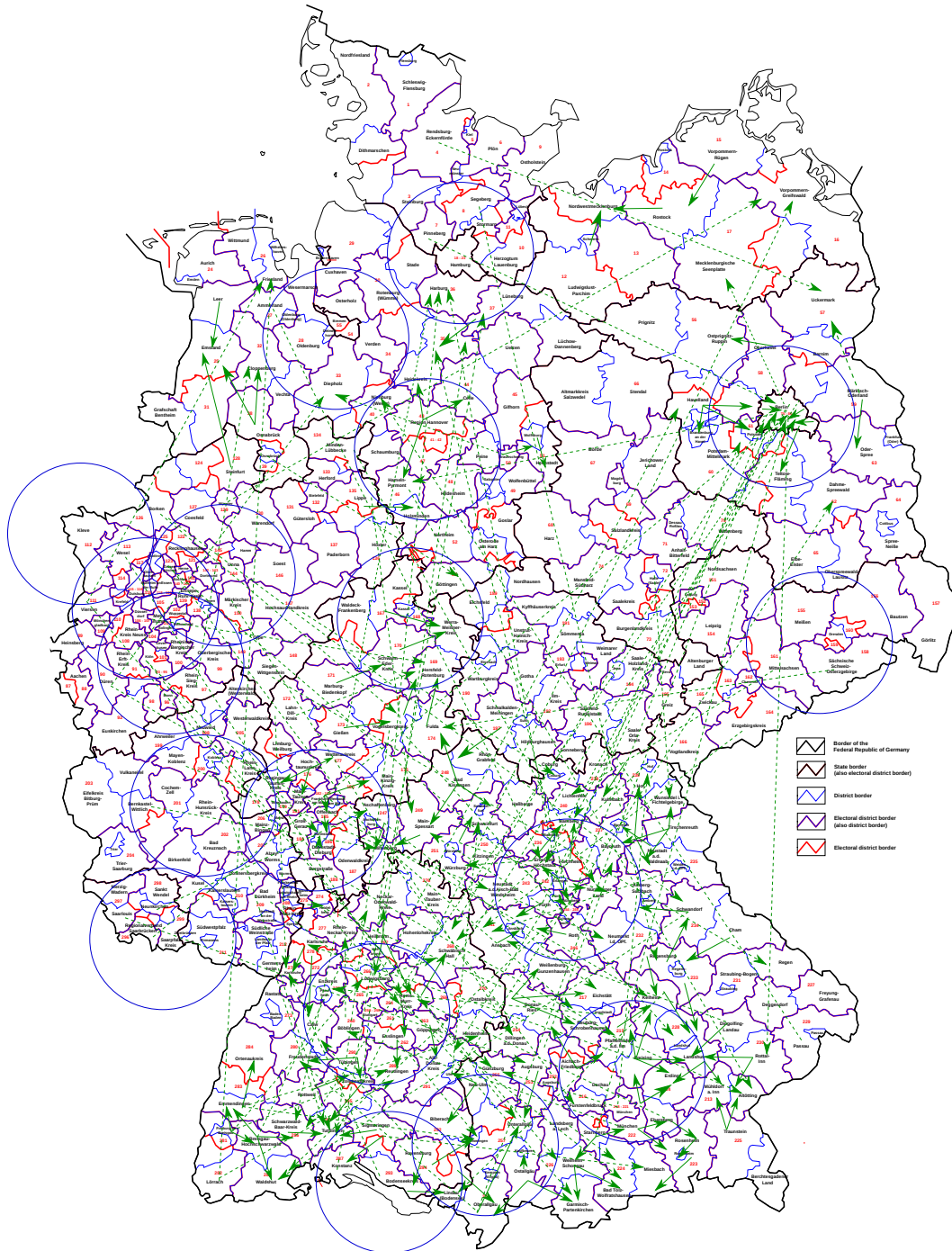Here we provide figure 3b enlarged for better visibility.

Figure 8: Detected causal districts for the spread of Covid-19, for each district, using the modified SyPI algorithm. Solid arrows depict causes that are neighbour districts (i.e., sharing a common border). Dashed arrows depict causes that are not. The majority of the detected non-neighbour causes are close to big cities with large airports (MUC, STR, TXL, FDH, FMM, NUE, HAM, FRA, HHN, HAJ, NRN, CGN, DUC, DMT, DRS, BRE, KSF, SCN), and the majority of the detected causes are neighbours to the target. Note that since the dashed arrows are significantly longer than the solid ones, the Figure at first glance seems to show mostly dashed arrows. This is misleading; for a numeric comparison, see Figure 4a. Blue cycles indicate 40km radius around the largest airports. For the district-level analysis, the default thresholds of SyPI were used $(0.01, 0.2)$.

9.6 Additional experiments including updated data until 26/09/2020

We update our analysis from the last time's available data, by including four months of daily reported Covid-19 infections per federal state until 26/09/2020.

The updated time series can be seen in Figure 9. We see that until September 26th, there is a second but smaller wave of infections, starting from mid July 2020.
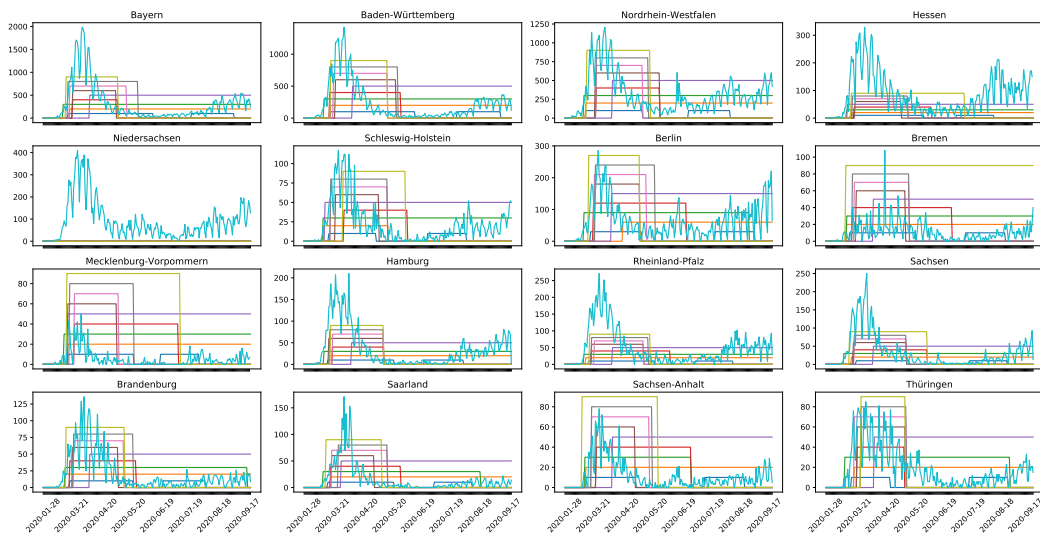

Figure 9: Daily reported Covid-19 infections per federal state until 26/09/2020.

As can be seen in Figure 10 including updated infection time series with four more months of data in our analysis, resulted in detected causes very close to the original detected ones until mid May 2020. Moreover, we observe that the newly detected causes are neighbour states, forming clear clusters of neighbouring causes.
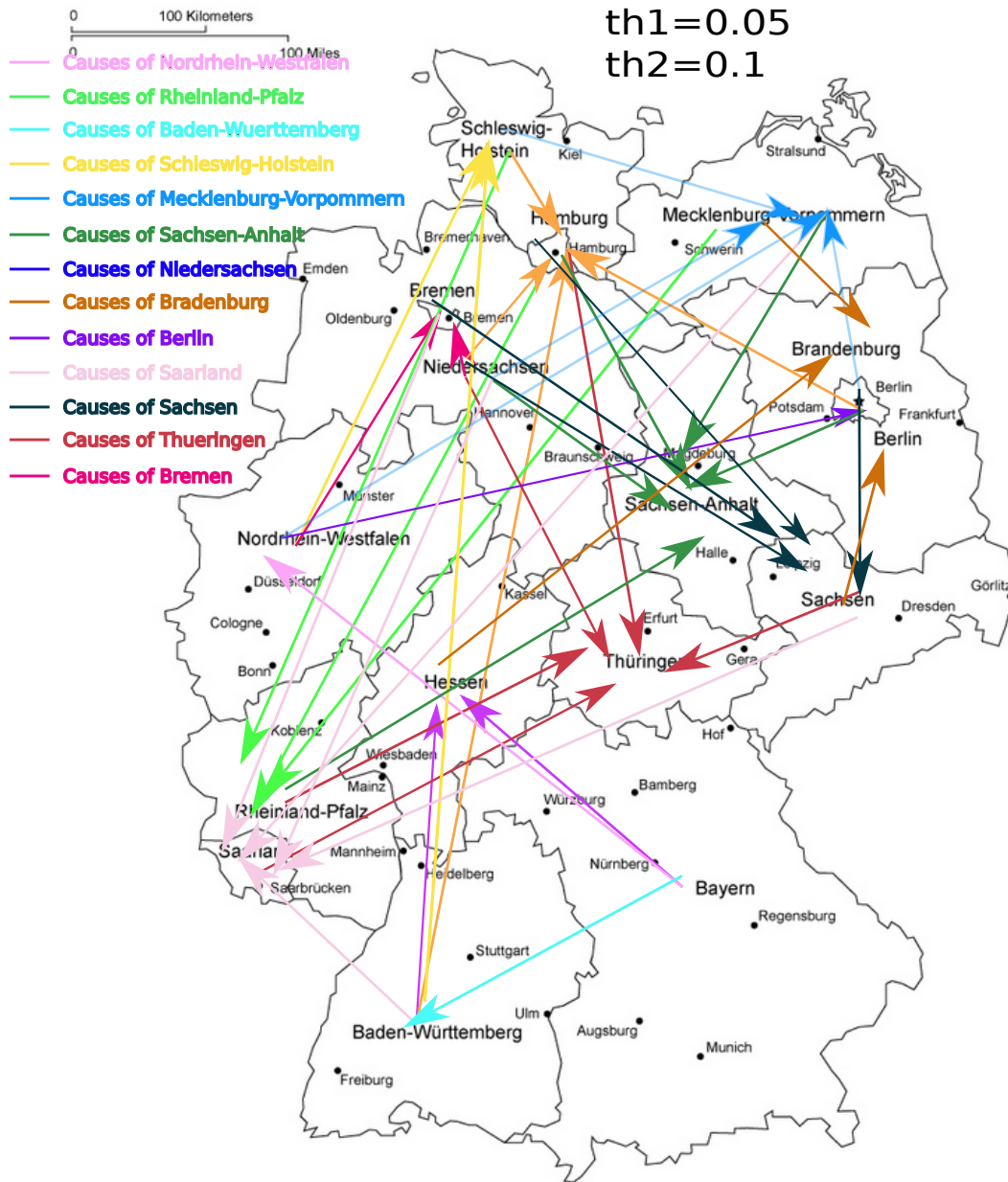
th1=0.05
th2=0.1

Figure 10: Updating the results including data from four more months since the first analysis, we see that the detected causes are very close to the originally detected ones and more clustered in neighbours.

At this point we attempt to re-evaluate the role of the updated NPIs as well. Since the ending date of each political measure was not always clearly stated for each federal state, we report the following disclaimers. Regarding the banning of visitors on hospitals: from the day that even one visitor was allowed, we considered the measure no longer active on the specific state. Moreover, in federal states where the banning of gatherings of more than 10 people was active, the banning of gathering of more than 2 people was also considered active, even if it was not explicitly stated as a separate measure by the state. Moreover, during the summer holidays that the schools were closed, the measure "closing of schools" was considered active. Since the universities did not open officially for courses, the measure for closing of the universities was considered active. Finally, regarding the banning of gatherings

of more than 1000 people, there seemed to be a difference between public events, private events, events outdoors, events indoors and an exception for the fans for the soccer league. We considered the measure active apart from the states that the attending of soccer in stadiums was allowed.

Taking into account the non pharmaceutical interventions as well, the additional data of four months resulted in the detected causes shown in Figure 11. As we can see, the closing of schools and universities are no longer the most prominent causal policies. Now, the measures most frequently detected as causal are the obligatory quarantine after the visit of risk areas, and the closing of restaurants. In terms of demographics, we observe that less arrows are detected, and that the federal states have causes that include at least one neighbour region. We stress again that cautious should be exercised in the interpretation of these new results, as the termination dates of some of the measures was very vague in most of the states. Therefore, we cannot exclude the possibility that the binary time series that correspond to the NPIs after 15th of May are not correct.
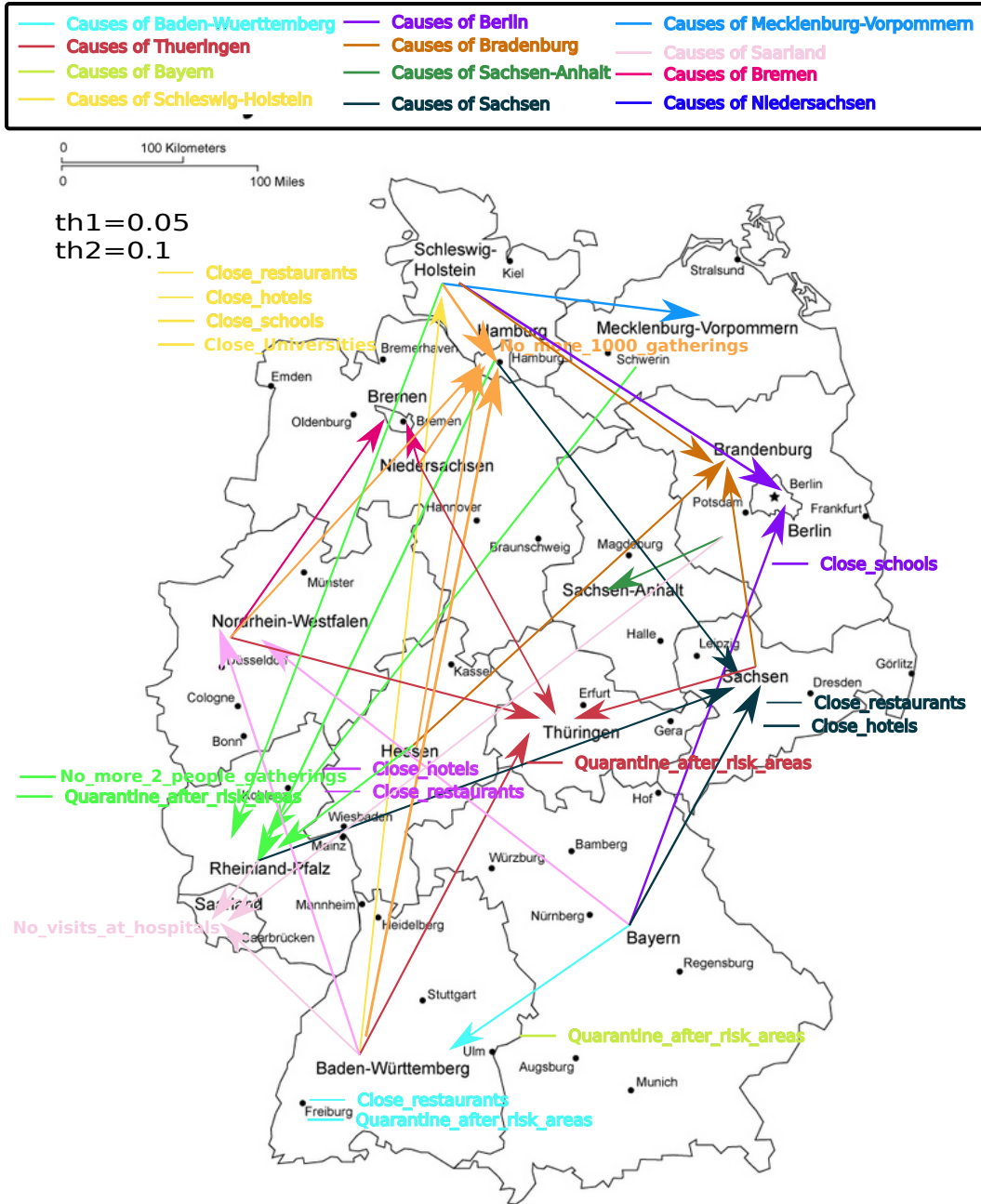
Figure 11: Updated results with infection numbers and NPIs until 26/09/2020, for thresholds (0.05, 0.1).