Projecting COVID-19 epidemic risk in Summer 2021 by French department

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RESUME

Les semaines à venir vont être cruciales pour déterminer les conditions et le calendrier d'une 4e vague de COVID-19 en France, sous la pression de la propagation rapide du variant Delta et de la diminution du rythme de vaccination. Les efforts de surveillance et de contrôle devraient anticiper une grande hétérogénéité géographique, en raison de schémas spatialement hétérogènes d'immunité au niveau de la population, de mobilité estivale et de surpeuplement, et de la présence du variant Delta. Nous quantifions ces facteurs en (i) définissant cinq mesures de risque, (ii) les utilisant pour profiler le risque épidémique dans chaque département de France métropolitaine, et (iii) les combinant en une seule mesure de risque global par département. Notre analyse montre que les départements du Sud-Ouest sont généralement les plus à risque. Cela est principalement dû à la combinaison de trois types de risques – le surpeuplement dû à la saison estivale, une immunité plus faible, et la présence de foyers du variant Delta. Nos mesures de risque peuvent aider à orienter l'allocation des ressources de surveillance et de contrôle, et à améliorer les efforts de vaccination.

SUMMARY

The upcoming weeks will be critical in shaping the conditions and timing of a 4th wave of COVID-19 in France, under the pressure of the rapidly spread of the Delta variant and the decrease in vaccination pace. Surveillance and control efforts should anticipate a large geographical heterogeneity, due to spatially heterogeneous patterns of infection-acquired immunity, vaccination, summer mobility, and presence of the Delta variant. We quantify these factors by (i) defining five risk metrics, (ii) using them to profile epidemic risk in each department of mainland France, and (iii) combining them into a single metric of overall risk per department. We find departments in the Southwest to be generally at highest risk. This is mainly due to the combination of three types of risk, namely crowding due to the summer season, lower

immunity, and presence of Delta variant hotspots. Our risk metrics can help guide the allocation of surveillance and control resources, and improve vaccination efforts.

INTRODUCTION

The COVID-19 situation in France is likely at a turning point. After several weeks of decrease in viral circulation, week 26 witnessed a marked increase in the case incidence in the 15-44 years old population[1]. Administration of the first doses is receding since several weeks[2], while the Delta variant rapidly progresses, with an estimated 43.2% of detected cases attributed to the L452R mutation in week 26[3]. A large heterogeneity across space is reported that may be further exacerbated by the rise of summer travels, increasing the mixing between different populations of varying levels of immunity and from areas characterized by diverse Delta presence.

Using hospitalization, COVID-19 incidence, PCR screening and vaccination data from official sources, and crowding and contact data from Facebook, we introduce 5 data-driven risk metrics at the departmental level, each highlighting different aspects contributing to the local epidemic risk:

1) Low local population-level immunity;
2) High mixing with residents of other departments with low population-level immunity;
3) Frequency of Delta variant among screened PCR tests;
4) High mixing with residents of other departments in which there is high incidence of the Delta variant;
5) Crowding: increased population during the summer season.

(1) identifies departments in which a large number of susceptible individuals may fuel outbreaks. (2) identifies departments whose residents may be exposed to cases generated in low-immunity departments. (3) identifies departments where outbreaks may be accelerated due to the Delta variant. (4) identifies departments whose residents may be exposed to the Delta variant. (5) identifies departments with an expected higher mixing due to summer travels.

Synthesizing these 5 risk metrics into an overall risk indicator for each department, we identify departments at higher risk that could help inform prioritization of surveillance and control efforts.

METHODS

Population-level immunity. We inferred cumulative infections in each department using hospitalizations data and screening data from Santé Publique France (SpF). We assumed a 7-day delay from infection to hospitalization, and hospitalization rates by variant reported in the literature[4-5]. We used vaccination data from the Assurance Maladie[6] providing injections history by type of vaccine. We combined immunity after infection and immunity due to vaccination in a single metric ρ_i, for each department i. This results in

$$\rho_i = 1 - (1 - v_i)(1 - \eta_i)$$

$$v_i = \sum_k \left(v_{1,k,i} \varepsilon_{1,k} + v_{2,k,i} \varepsilon_{2,k} \right)$$

Where η_i is immunity after infection, $v_{1,k}, v_{2,k}$ are the proportion of 1st vaccinations and complete vaccinations for vaccine k, among Pfizer/BioNTech, Moderna, AstraZeneca, Janssen (the latter contributing only to complete vaccinations). $\varepsilon_{1,k}, \varepsilon_{2,k}$ are the efficacy of 1st and complete vaccination schemes, as reported in the literature[7-9].

To project vaccination coverage in the near future, we designed two scenarios:

- S1, projecting future 2nd vaccinations from reported 1st vaccinations to date, and assuming that no additional first injections are administered.
- S2, projecting future 1st vaccinations assuming that the rates of new vaccinations in each department is the same as that observed in June, and projecting future 2nd vaccinations from reported and projected 1st vaccinations.

Results shown in the figures are for the vaccination rollout scenario S1. In the Appendix, we show a comparison between the results obtained in the two scenarios.

Mobility and crowding. We used human mobility and population data provided through a partnership with Facebook Data For Good[10]. These data inform on the number of individuals in each department of mainland France (excluding Corsica), and on the level of mixing (potential contacts) between residents of any two departments. From mixing data, we build the matrix p_{ij}, which encodes the average number of contacts that the average resident of department i has with residents of department j, in any given day of July and August 2021. To infer mobility after the present date, we used data from the same period in 2020, i.e. we assume that mobility and contacts during summer 2021 follows the patterns observed in summer 2020.

Risk metrics and overall risk.

- Susceptibility in every department is computed from estimated population-level immunity: $s_i = 1 - \rho_i$.

- Relative immunity difference among contacts from other departments is $\rho_i^{(j)} = \frac{\rho_i - \rho_i^{(r)}}{\rho_i + \rho_i^{(r)}}$, where

  $\rho_i^{(r)} = \frac{\sum \rho_j p_{ij}}{\sum p_{ij}}$, which contains the mixing matrix.

- Proportion of Delta variant comes from screening data from SpF from the last week of June. For each department we use the fraction of Delta-positive screenings among all screenings: Δ_i.

- Exposure to the Delta variant from other departments is computed as the likelihood that an infected contact from another department screens positive to the Delta variant, as follows: $\Delta_i^{(j)} = \frac{\Delta_i^{(r)} - \Delta_i}{\Delta_i^{(r)} + \Delta_i}$,

 where $\Delta_i^{(r)} = \frac{\sum x_{j,\Delta} p_{ij}}{\sum x_j p_{ij}}$.

- Crowding C_i is computed as the relative difference in population, with respect to a baseline set to the 2nd week of May. Negative values (decreased mobility) are clipped to zero.

Overall risk is computed as the sum of the standardized (mean=0, variance=1) values of the five risk indicators. The result is then mapped between zero and one, with zero corresponding to the lowest risk, one corresponding to the highest risk.

RESULTS
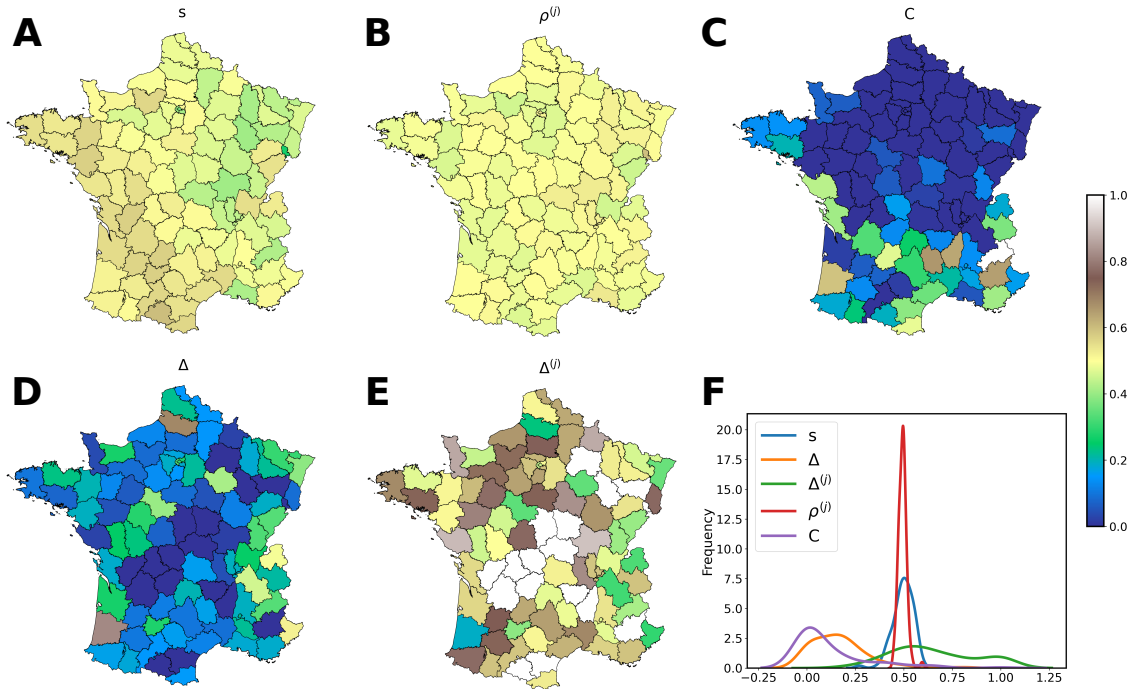
Figure 1. Risk metrics. We defined five metrics corresponding to the five types of risk identified (see also Methods). A) susceptibility: shows the fraction of susceptible individuals in each departments (excluding Corsica); B) relative immunity difference shows the relative difference in immunity between residents and their contacts from other departments; C) crowding: shows the relative increase in population during summer; D) proportion of Delta variant: shows the fraction of Delta-variant cases; E) exposure to the Delta variant from other departments: shows the probability that a case from another department is infected with the Delta variant. For the definition of the risk metrics see Methods. F) shows the distribution of each metric across departments.
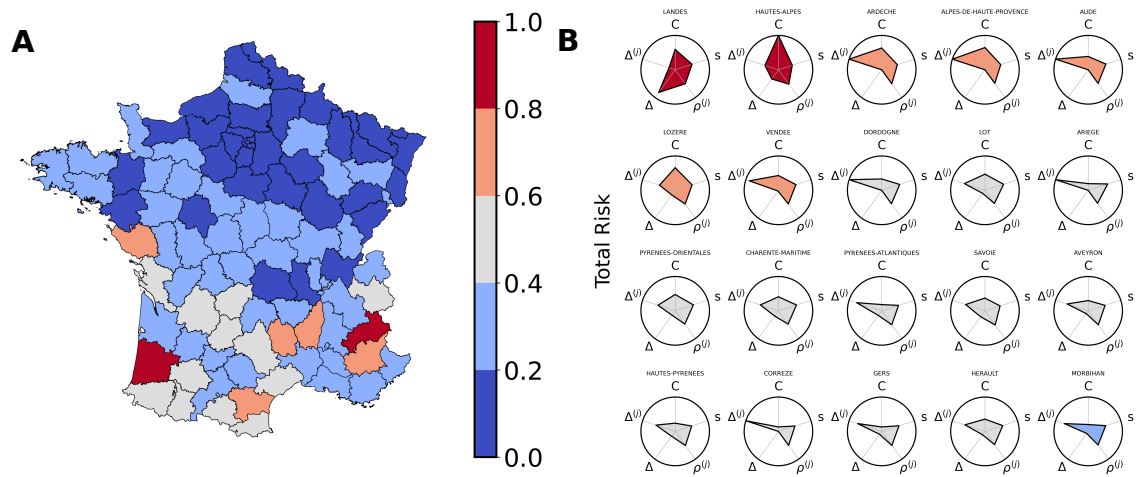
Figure 2. Overall risk. We used our risk metrics to define a synthetic indicator of overall risk (see Methods). A) shows overall risk in each department, binned in 5 intervals: 0-to-0.2 (dark blue), 0.2-to-0.4 (light blue), 0.4-to-0.6 (gray), 0.6-to-0.8 (orange), 0.8-to-1 (red). B) shows the composition of risk in the top 20 departments with the highest overall risk. The values of the five risk metrics are shown in the radar plots. Radar plots are colored according to their overall risk bin.

KEY FINDINGS

- We computed 5 risk metrics in each department to measure risk related to population-level susceptibility, mobility, crowding, presence of the Delta variant (**Figure 1**). The following table lists the top three department (highest risk) for each risk metric:

risk metric	top three departments
s (susceptibility)	1. ARIEGE 2. TARN-ET-GARONNE 3. CHARENTE
$\rho^{(j)}$ (relative immunity difference)	1. TERRITOIRE DE BELFORT 2. PARIS 3. BOUCHES-DU-RHONE
c (crowding)	1. HAUTES-ALPES 2. LOZERE 3. ALPES-DE-HAUTE-PROVENCE
Δ (frequency of the Delta variant)	1. LANDES 2. SOMME 3. ALPES-MARITIMES
$\Delta^{(j)}$ (exposure to Delta from other departments)	1. ALLIER 2. DORDOGNE 3. HAUTE-MARNE

- Values are very heterogeneous across departments for the risk metrics related to crowding (c), and to the Delta variant, including both the local frequency (Δ) and the exposure to the variant through mobility ($\Delta^{(j)}$). Visible heterogeneity is observable for the risk factor related to susceptibility (s), whereas lower heterogeneity across space is estimated for the relative immunity difference across departments due to mobility ($\rho^{(j)}$).

- Susceptibility s shows a spatial gradient from NE (lower susceptibility), to SW (higher susceptibility). This is mostly due to infection-acquired immunity, as the epidemic impacted the NE more during the successive waves, leading to a higher estimated attack rate (see **Figure** S1 in Appendix). Crowding c exhibits a spatial gradient from North (lower crowding), to South (higher crowding), showing a net Southward population displacement during summer, to the coasts and mountain regions. Both Δ, $\Delta^{(j)}$ (risk due to local Delta frequency, and risk due to contacts with departments with high Delta frequency, respectively) are patchy, with no visible radial trend. This may be the concurrent outcome of two contributions: past seeding events with importations occurring at different times in different places; long-range mobility providing mixing opportunities between departments that are distant but connected by large mobility flows.

- We combined the five risk metrics into one synthetic metric of overall risk for each department (**Figure 2**). Overall risk can be used to rank departments to prioritize surveillance and control, and vaccination efforts. Overall risk is estimated to be higher in the South – Southwest of France, with departments located close to the Alps and Pyrenees, on the western Mediterranean coast, on the southern and central Atlantic coast, and in the inland regions of Nouvelle-Aquitaine and Occitanie. Among the top 10 departments with higher overall risk, 4 departments are in Occitanie, 2 in Nouvelle-Aquitaine, 2 in Provence-Alpes-Côte d'Azur, 1 in Auvergne-Rhône-Alpes, 1 in Pays de la Loire.

- Overall risk inherits spatial gradients from susceptibility (NE-SW) and crowding patterns (N-S), leading to lower estimated risk in the North – Northeast compared to the South – Southwest of France. However, departments at higher overall risk exhibit different risk profiles. Landes has the highest overall risk of all, dominated by the local prevalence of the Delta variant among screened cases. Hautes-Alpes has the 2nd highest overall risk, and risk is dominated by high crowding during summer. Ardèche, Alpes-de-Haute-Provence, Aude are third, fourth and fifth. Their risk is dominated by possible exposure to Delta variant from other departments through mobility. Many among the top-20 departments by overall risk show high risk of exposure to Delta variant from other departments. Lozère is fifth in the ranking of the overall risk, and risk there comes from multiple sources: high local susceptibility, crowding, low immunity among contacts in outside departments, exposure to Delta variant from other departments.

- Our ranking of departments by overall risk is robust across different scenarios of projected vaccination rates in the following months (see Appendix Figure S2). This suggests that current heterogeneity in vaccination rollout and assumed rhythms of vaccination for the upcoming weeks are not large enough to affect the ranking in the department risk.

LIMITATIONS

- Our estimates rely on the assumption that mobility and crowding during late July – August 2021 are similar to the same period in 2020.

- Our immunity projections do not account for infections occurring later than the current date. They should, however, have little impact on immunity given the currently low incidence. This is also confirmed by the robustness of results across different vaccination rollout scenarios.

- We do not consider age structure in this assessment. This may impact our inference of infection-acquired immunity per department in presence of substantial heterogeneities of age profiles of department populations. Concerning displacements, our previous work showed that mobility difference across broad age classes were relatively small during movement restrictions[11]. However, younger population strata may be more mobile and more susceptible (lower vaccination coverage) during summer holidays. Finally, this risk assessment does not focus on the healthcare impact.

- This report provides an assessment of the risk based on the current situation and the evolving behavior registered during last summer. Changes in these conditions compared to last summer (e.g., due to recommendations, adaptive behaviors, novel policies) will affect these findings.

- Our report covers only the departments of mainland France, excluding Corsica.

- The choice of the five metrics is arbitrary, and so is their synthesis as overall risk. They nonetheless encode the main factors we expect to play a crucial role in this epidemic phase.

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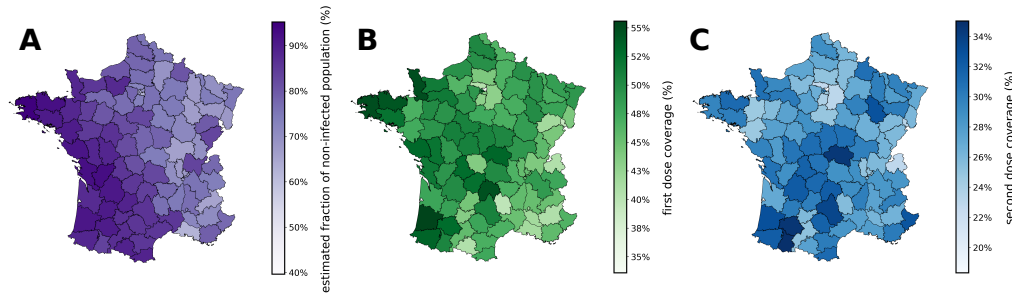
Figure S1. Sources of immunity. A) shows current estimated fraction of non-infected population. B) shows current 1-dose vaccine coverage; C) shows the fraction of fully vaccinated individuals.

$r = 0.98 \ (p_v = 0.0)$
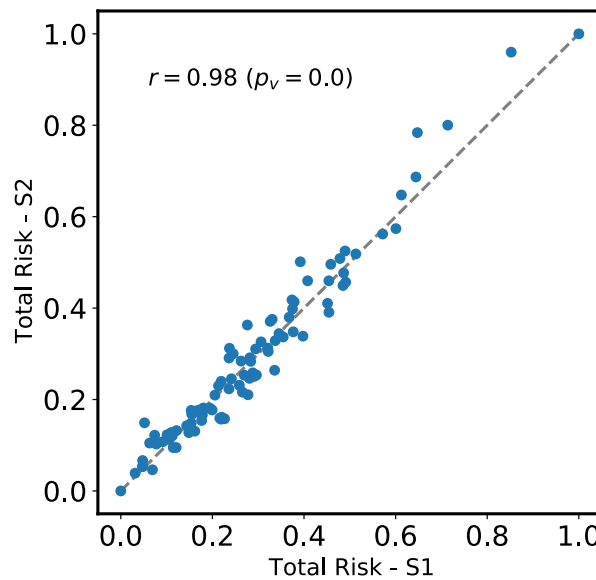
Figure S2. Comparing immunity scenarios. We tested two immunity scenarios. S1 includes infection-acquired immunity, complete vaccinations to date, 1st-dose vaccinations to date, projected complete vaccinations from recorded 1st doses. S2 includes infection-acquired immunity, complete vaccinations to date, 1st-dose vaccinations to date, projected 1st doses assuming that vaccination rate in each department is the same as the one recorded in June, projected complete vaccinations from recorded and projected 1st doses. The figure compares overall risk in the two immunity scenarios (S1 vs S2). Pearson coefficient is 0.98, Kendall-tau coefficient is 0.87.