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# Optimising geographical accessibility to primary health care: a geospatial analysis of community health posts and community health workers in Niger

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## ABSTRACT

**Background** Little is known about the contribution of community health posts and community health workers (CHWs) to geographical accessibility of primary healthcare (PHC) services at community level and strategies for optimising geographical accessibility to these services.

**Methods** Using a complete georeferenced census of community health posts and CHWs in Niger and other high-resolution spatial datasets, we modelled travel times to community health posts and CHWs between 2000 and 2013, accounting for training, commodities and maximum population capacity. We estimated additional CHWs needed to optimise geographical accessibility of the population beyond the reach of the existing community health post network. We assessed the efficiency of geographical targeting of the existing community health post network compared with networks designed to optimise geographical targeting of the estimated population, under-5 deaths and *Plasmodium falciparum* malaria cases.

**Results** The per cent of the population within 60-minute walking to the nearest community health post with a CHW increased from 0.0% to 17.5% between 2000 and 2013. An estimated 10.4 million people (58.5%) remained beyond a 60-minute catchment of community health posts. Optimal deployment of 7741 additional CHWs could increase geographical coverage from 41.5% to 82.9%. Geographical targeting of the existing community health post network was inefficient but optimised networks could improve efficiency by 32.3%–47.1%, depending on targeting metric.

**Interpretations** We provide the first estimates of geographical accessibility to community health posts and CHWs at national scale in Niger, highlighting improvements between 2000 and 2013, geographies where gaps remained and approaches for optimising geographical accessibility to PHC services at community level.

## Key questions

### What is already known?

- Previous studies have estimated geographical accessibility (as travel time) to health facilities, geographical accessibility to community health workers (CHWs) for subnational areas only, and assessed efficiency of the distribution of hospitals in low/middle-income countries.

### What are the new findings?

- The per cent of the population within 60-minute walking to the nearest community health post with a paid, full-time CHW increased from 0.0% to 17.5% between 2000 and 2013, with 15.5% within 60-minute walking to the nearest health post with a CHW trained on integrated community case management (iCCM)—making primary healthcare (PHC) services at community level and iCCM, specifically, geographically accessible for an estimated 2.3 million and 2.0 million additional people, respectively.
- An estimated 10.4 million people (58.5%) remained beyond a 60-minute catchment of community health posts in 2013, with important variation across subnational geographies, training of CHWs and availability of essential commodities.
- Optimal deployment of 7741 additional CHWs could increase geographical coverage of the estimated total population from 41.5% to 82.9%, providing physical access to PHC services at community level for an additional 7.4 million people not covered.
- Optimised networks of community health posts increased efficiency of geographical targeting compared with the existing network by 32.3%–47.1%, depending on targeting metric.

## BACKGROUND

Community health workers (CHWs) can play an important role in improving equitable access to quality primary healthcare (PHC) at community level in the context of Universal Health Coverage as front-line service providers and as a trusted bridge between health systems and communities.[1–3] CHWs typically focus on maternal, newborn and

## Key questions

### What do the new findings imply?

- The scale-up of community health posts staffed by paid, full-time CHWs improved geographical accessibility to PHC services at community level, including iCCM, between 2000 and 2013; however, efficiency of geographical targeting of community health posts was suboptimal, implying—that had scale-up been optimised—significant improvements in population coverage could have been realised, with cost-savings reinvested in further scale-up and health systems strengthening.
- The approaches described in this study could inform retargeting of the existing network of community health posts and future scale-up efforts to optimise geographical accessibility of PHC services at community level in Niger and could be adapted to similar contexts within sub-Saharan Africa.

child health and nutrition, providing a range of preventive, health promotion and curative services—including single disease or integrated community case management (iCCM).[4] iCCM is the provision of integrated case management services for two or more childhood illnesses among children less than 5 years of age by CHWs, where geographical accessibility (ie, physical access) to health facility-based case management services is limited.[5] In Niger, the Ministry of Public Health (MOPH) scaled up community health posts staffed by paid, full-time CHWs from the early 2000s. A midterm review of the National Community Health Strategy is planned for 2022, a Global Financing Facility (GFF) investment case is being developed and discussions on a new Health Sector Development Plan (2022–2026) are underway. Given this context, discussion on optimising geographical accessibility to PHC at community level is highly relevant. Previous studies in sub-Saharan Africa have estimated geographical accessibility (as travel time) to health facilities at national level[6 7] and CHWs for subnational areas only.[8–11] The efficiency of geographical targeting of health service locations has been assessed for hospitals in low-income and middle-income countries, but this did not include community health posts or CHWs.[12] In this article, we describe for the first time at national scale the number and geographical distribution of community health posts and CHWs in Niger. We estimate their contribution to geographical accessibility to PHC services at community level, efficiency of geographical targeting of the community health posts and needs for further scale-up of CHWs with the aim of optimising PHC at community level.

## METHODS

In this section, we describe the study settings, data and methods used. Online supplemental appendix 1 provides a simplified analysis flow and additional details on the data and methods.

### Study settings

During the period of focus of this study, 2000–2013, Niger was divided into four political administrative levels: communes, departments, regions and national.[13] The health system of Niger included a public and private sector organised in a decentralised, pyramidal structure with three administrative levels overseen by the MOPH. Details on the health system are provided in online supplemental appendix 1. Our analysis focuses on the first level (periphery) of the public sector, which is central to PHC at community level. The first level of the public sector is made up of referral facilities called *centre de santé intégré* (CSI) and community health posts called *case de santé* (CS). As of December 2012, there were 856 CSI offering a minimum package of services, focused on PHC, referral from and counter-referral to the CS, and supervision of the CS.[13] CSI were typically staffed by nurses—and in certain large communes by a generalist doctor and midwives[13]—and, according to national norms, were intended to serve a maximum population of 5000–15 000 inhabitants, depending on population density.[14] According to national norms, CS were intended to be situated 5 km beyond a supervising CSI and served a population of 2500–5000.[14] CS provided a minimum package of services, focused on PHC at community level, including prevention services, health promotion services, and services for reproductive, maternal, newborn and child health, including iCCM. CS were typically staffed by a cadre of paid, full-time CHWs called *agent de santé communautaire* (ASC) and/or, in some cases, a nurse.[14] CS and ASC were scaled up between 2000 and 2013—a period of considerable progress on under-5 mortality.[15 16] As of December 2012, there were 2451 CS.[13] Some CS were supported by one or more volunteer CHWs called *relais communautaire* (RC), providing health promotion and prevention interventions in the communities within the catchment area (typically a 5 km radius) of the CS.[13 14] The MOPH in Niger plans to scale up RC—some targeted to communities beyond 5 km of CS or CSI to provide a standard package of preventive, promotive and curative services, including iCCM.[17]

### Data

To inform our models of travel time to service delivery locations, we obtained spatial datasets for the following inputs: administrative boundaries (levels 0–3),[18] a 2013 georeferenced census of health service delivery networks (CSI, CS and ASC),[19] digital elevation model,[20] land cover,[21] roads,[22] rivers and other water bodies (treated as barriers to movement where no road crossed),[23] and travel scenarios. To inform our analysis of accessibility coverage, geographical coverage, RC scale-up and efficiency of geographical targeting of the CS, we obtained modelled estimates for population counts for 2000–2013[24] and 2015.[25] Also to inform our analysis of the efficiency of geographical targeting of the CS, we obtained modelled estimates for the annual mean under-5 mortality rate in 2013[26] and modelled estimates for the annual mean incidence of *Plasmodium falciparum* (*Pf*) malaria among all ages (0–99 years) in 2013,[27] as PHC services provided through the CS are intended to address under-5 mortality and malaria[14] —with the latter being a main cause for curative consultations among children under-5 in Niger.[13] We prepared the input datasets in the projected coordinate reference system WGS 84/UTM zone 32N (EPSG: 32632) for Niger at 100×100 m resolution for our analysis of accessibility coverage and 1×1 km for our analysis of geographical coverage, targeting and scale-up. Further details are in online supplemental appendix 1.

We prepared travel speed tables for two travel scenarios: (1) walking in dry conditions and (2) walking to the nearest road and then using motorised transportation (assumed to be immediately available) in dry conditions. We set travel speeds by travel scenario for each land cover class and road class. Travel speeds were adapted from previous studies and experience in Niger and broader sub-Saharan Africa.[7 28]

### Assessing geographical accessibility

We assessed geographical accessibility through two measures: accessibility coverage and geographical coverage.

We defined accessibility coverage as the estimated percentage of people within a given travel time to the nearest health service delivery location of a given health service delivery network, accounting for travel speeds of different modes of transportation over different land cover classes and slope, with the direction of travel toward the health service delivery location.[28] We estimated accessibility coverage at 100×100 m resolution for the CSI and CS-ASC (includes CS with or without ASC and the small number of ASC sites not within a CS) networks in 2013—and for the ASC network by gender, year of deployment (2000–2013), training, and availability of essential commodities—using 30-minute and 60-minute cut-offs for administrative levels 0–3 and the two travel scenarios. We used 30-minute and 60-minute cut-offs as previous analyses have shown care-seeking delays as a function of travel time after these cut-offs[29] and they are clinically relevant (eg, for prompt treatment of severe illness).[30] The analysis was constrained to national borders but allowed for travel across subnational administrative boundaries. We used the 'geographic accessibility' module within AccessMod 5 (V.5.6.48)[28] to calculate travel time layers and the 'zonal statistics' module to calculate the zonal statistics for each travel time layer by administrative level.

We defined geographical coverage as the theoretical catchment area of a health service delivery location, within a maximum travel time, accounting for the mode of transportation and the maximum population coverage capacity of the type of health service delivery location.[28] We used the 'geographic coverage' module of AccessMod 5 (V.5.6.48)[28] to estimate geographical coverage for the CSI and CS-ASC networks in 2013 at 1×1 km resolution for the two travel scenarios. The maximum travel time was set at 60 min. The maximum population capacity was set at 10 000 for CSI and 2500 for CS-ASC based on norms of the MOPH of Niger.[14] The maximum extent of a catchment was therefore delimited by the maximum travel time of 60 min except in cases where the estimated population in the catchment exceeded the maximum population capacity of the health service delivery location—in which case the extent of the catchment was smaller than the maximum travel time and was defined by the area containing the estimated population, up to the maximum population capacity.

### Assessing geographical coverage of a hypothetical scale-up network of RC

To estimate the number of RC needed to maximise geographical accessibility of the population beyond the geographical coverage of the existing CSI and CS-ASC networks, we simulated a hypothetical network of RC in grid cells with at least 250 people in 2013 located beyond the geographical coverage of the existing CSI and CS-ASC networks at 1×1 km resolution, using a ratio of 1 RC per 1000 population (with a minimum threshold of 250 people to allocate 1 RC). We conducted a geographical coverage analysis at 1×1 km resolution to estimate the per cent of the estimated residual population that could be covered by the hypothetical RC network, within a maximum travel time of 60-minute walking to the nearest RC and maximum population capacity of 1000 for each RC.

### Assessing efficiency of geographical targeting

We assessed the efficiency of geographical targeting of the CS-ASC network, using the concept of technical efficiency. We defined technical efficiency as the maximisation of a health outcome (geographical coverage) for a given set of inputs (the number of CS-ASC).[31] We used the estimated population, under-5 deaths and *Pf* malaria cases (all ages) beyond the geographical coverage (60-minute walking) of the CSI network in 2013—hereafter called the estimated residual population, under-5 deaths and *Pf* malaria cases, respectively—as the 'populations' to target in our geographical targeting analysis. We assessed the efficiency of geographical targeting of the existing CS-ASC network with three metrics: (a) geographical coverage of the estimated residual population; (b) geographical coverage of the estimated residual under-5 deaths; and (c) geographical coverage of the estimated residual *Pf* malaria cases (all ages) beyond the catchment of the CSI network in 2013 at 1×1 km resolution compared with three hypothetical CS-ASC networks designed to optimise metrics a–c. For (a) we compared the existing CS-ASC network (n=2550) with the 2550 CS-ASC from the hypothetical network that maximised geographical coverage of the targeted population, using the MOPH norm of 1 CS-ASC per 2500 population as the maximum population capacity. There is no MOPH norm for the ratio of CS-ASC per under-5 deaths or *Pf* malaria cases. Assuming one CS-ASC could cover all estimated under-5 deaths or *Pf* malaria cases within their catchment

**Table 1** Accessibility coverage of the front-line health facility and ASC networks

| | Walking | | | | Walking+motorised transportation | | | |
|---|---|---|---|---|---|---|---|---|
| | Covered 30 min (no) | Covered 60 min (no) | Covered 30 min (%) | Covered 60 min (%) | Covered 30 min (no) | Covered 60 min (no) | Covered 30 min (%) | Covered 60 min (%) |
| CSI+CS-ASC | 7 555 209 | 9 702 395 | 41.8 | 53.7 | 10 049 232 | 11 847 974 | 55.6 | 65.5 |
| CSI | 4 454 595 | 5 617 195 | 24.6 | 31.1 | 7 499 712 | 9 375 295 | 41.5 | 51.9 |
| CS-ASC | 3 724 166 | 5 516 196 | 20.6 | 30.5 | 8 552 971 | 10 917 747 | 47.3 | 60.4 |
| ASC | 1 930 318 | 3 156 228 | 10.7 | 17.5 | 6 177 540 | 9 228 791 | 34.2 | 51.0 |
| Female ASC | 624 548 | 1 115 902 | 3.5 | 6.2 | 3 333 890 | 6 228 099 | 18.4 | 34.4 |
| Male ASC | 1 403 743 | 2 352 088 | 7.8 | 13.0 | 4 710 547 | 8 290 546 | 26.1 | 45.9 |
| ASC trained on iCCM | 1 681 118 | 2 807 629 | 9.3 | 15.5 | 5 789 678 | 8 866 791 | 32.0 | 49.0 |
| Additional contribution ASC | 1 598 393 | 2 312 056 | 8.8 | 12.8 | 3 333 890 | 6 228 099 | 18.4 | 34.4 |
| Additional contribution ASC trained on iCCM | 1 365 053 | 1 997 636 | 7.5 | 11.0 | 860 150 | 1 343 604 | 4.8 | 7.4 |

ASC, agent de santé communautaire; CS, case de santé; CSI, centre de santé intégré; iCCM, integrated community case management.

regardless of population size would be unrealistic. Instead of making this unrealistic assumption, for metrics (b) and (c) we based the number of CS-ASC required for the existing CS-ASC network and the hypothetical CS-ASC network on the estimated number of CS-ASC needed to cover the estimated residual population in each catchment, using the MOPH norm of 1 CS-ASC per 2500 population. We then compared the estimated geographical coverage attained through the first 2550 CS-ASC of the existing CS-ASC network to the first 2550 CS-ASC of the hypothetical CS-ASC network designed to optimise metrics b–c. We assessed the potential effect of uncertainty of the estimates for under-5 deaths and *Pf* malaria cases among all ages on interpretation of our targeting results (see online supplemental appendices 1 and 7).

### Patient and public involvement

We did not involve patients or the public in this study.

## RESULTS

### Accessibility coverage

Accessibility coverage of the ASC network increased from 0.0% to 17.5% between 2000 and 2013, with large variation at subnational levels, given a 60-minute cut-off and walking scenario (table 1, figure 1, online supplemental

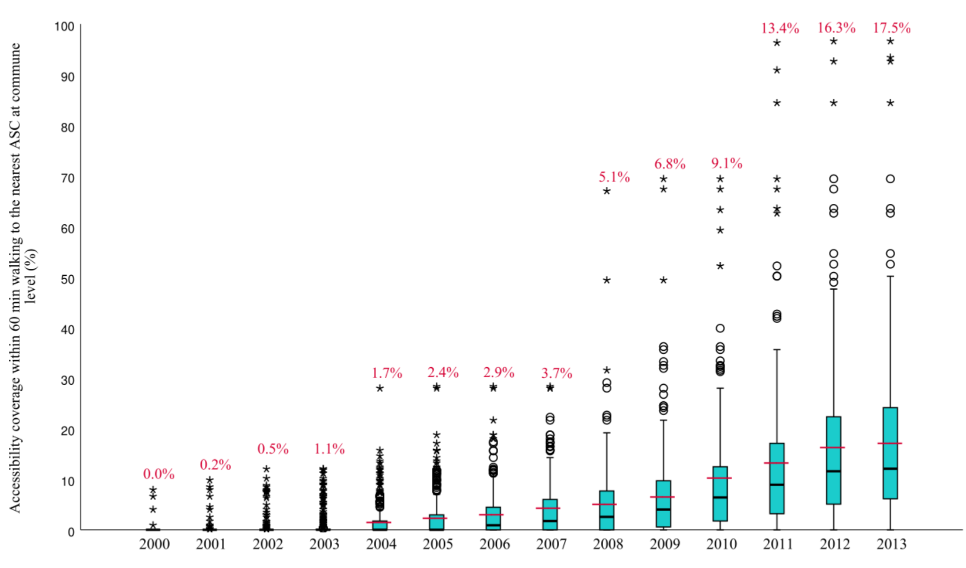


**Figure 1** Median and interquartile range of the percent of the population within 60 minutes walking of an ASC at commune level (administrative level 3) between 2000-2013 at 100m x 100m resolution. Black lines indicate the median at commune level. Blue boxes represent the interquartile range at commune level. Circles and stars indicate communes outside of the interquartile range. Red lines and percentages indicate the national mean. ASC, Agent de santé communautaire.

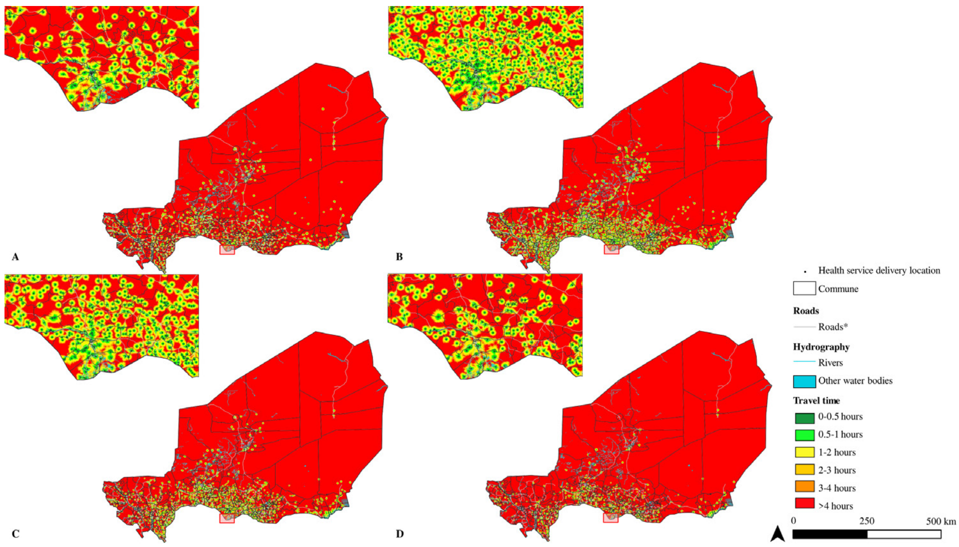


**Figure 2** Geographic accessibility (travel time in minutes, walking in dry conditions) in 2013 at 100m x 100m resolution for A) *Centre de santé intégrée*, n=839; B) *Case de santé / Agent de santé communautaire*, n=2550; C) *Agent de santé communautaire*, n=1457; D) and D) *Agent de santé communautaire* trained on iCCM, n=1214. Inset near Madarounfa commune in Maradi region. *For visualization purposes road classes limited to motorway, trunk, primary, secondary and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands. iCCM, integrated community case managment.

appendix 2). Online supplemental videos 1 and 2 show the evolution of accessibility coverage of the ASC network between 2000 and 2013 by mode of transportation.

Accessibility coverage of the ASC network varied by gender of the ASC and training on specific interventions (table 1, online supplemental appendix 2 and figure 2A–L). Accessibility coverage of the ASC network trained on iCCM was 15.5% in 2013, given a 60-minute cut-off and walking scenario (table 1, figure 2D). The estimated additional contribution of the ASC network and ASC network trained on iCCM to accessibility coverage beyond the accessibility coverage of the existing CSI and CS (without ASC) networks combined, given a 60-minute cut-off and walking scenario, was 12.8% and 11.0%, covering an estimated 2.3 million and 2.0 million additional people, respectively (table 1).

Accessibility coverage in 2013, given a 60-minute cut-off and walking scenario, was 31.1% for the CSI network, 30.5% for the CS-ASC network and 53.7% for the combined CSI+CS-ASC network (table 1 and figure 2A–D). An estimated 8.3 million people (58.2%) remained beyond 60-minute walking to the nearest front-line health facility or ASC, without considering the maximum population capacity of these networks. Accessibility coverage of the CS network was lower when we considered availability of trained human resources (nurse or ASC) and essential commodities (online supplemental appendix 2 and figure 3A–G). Accessibility coverage of all health service delivery networks was higher when considering the walking plus motorised transportation travel scenario (online supplemental appendix 2 and figure 4A–F). We provide detailed results by administrative area in online supplemental appendix 2, tab 'Detailed_Results'.

### Geographical coverage

Geographical coverage of the estimated total population in 2013 by the CSI network was 22.1%, assuming a walking scenario with a 60-minute catchment and maximum population capacity of 10 000 per CSI (figure 3 and online supplemental appendix 3, tab 'Summary'). Geographical coverage of the total estimated population in 2013 by the CS-ASC network was 19.4%, assuming a walking scenario with a 60-minute catchment and maximum population capacity of 2500 per CS-ASC (figure 3, online supplemental figure 3). Geographical coverage of the estimated residual population beyond the geographical coverage of the CSI network in 2013 by the CS-ASC network was 25.8%, providing an estimated 3·5 million additional people with physical access to PHC services, with important variation by region (online supplemental appendix 3, tab 'Summary' and online supplemental figure 6). An estimated 58.5% of the population in 2013—10.4 million people, predominantly rural—were beyond the geographical coverage of the combined CSI and CS-ASC networks, with 81.1% of the total uncovered population concentrated in the regions of Zinder, Maradi, Tillabéri and Tahoua (online supplemental figure 6B,C).

### Geographical coverage of a hypothetical scale-up network of RC

A hypothetical network of 7741 RC in 6806 catchments with a maximum population capacity of 1000 people per RC, targeting 1×1 km cells with at least 250 people located beyond the geographical coverage of the existing CSI and CS-ASC networks, could cover 76.8% of this estimated residual population—providing physical access to PHC services for an estimated 7.4 million additional people

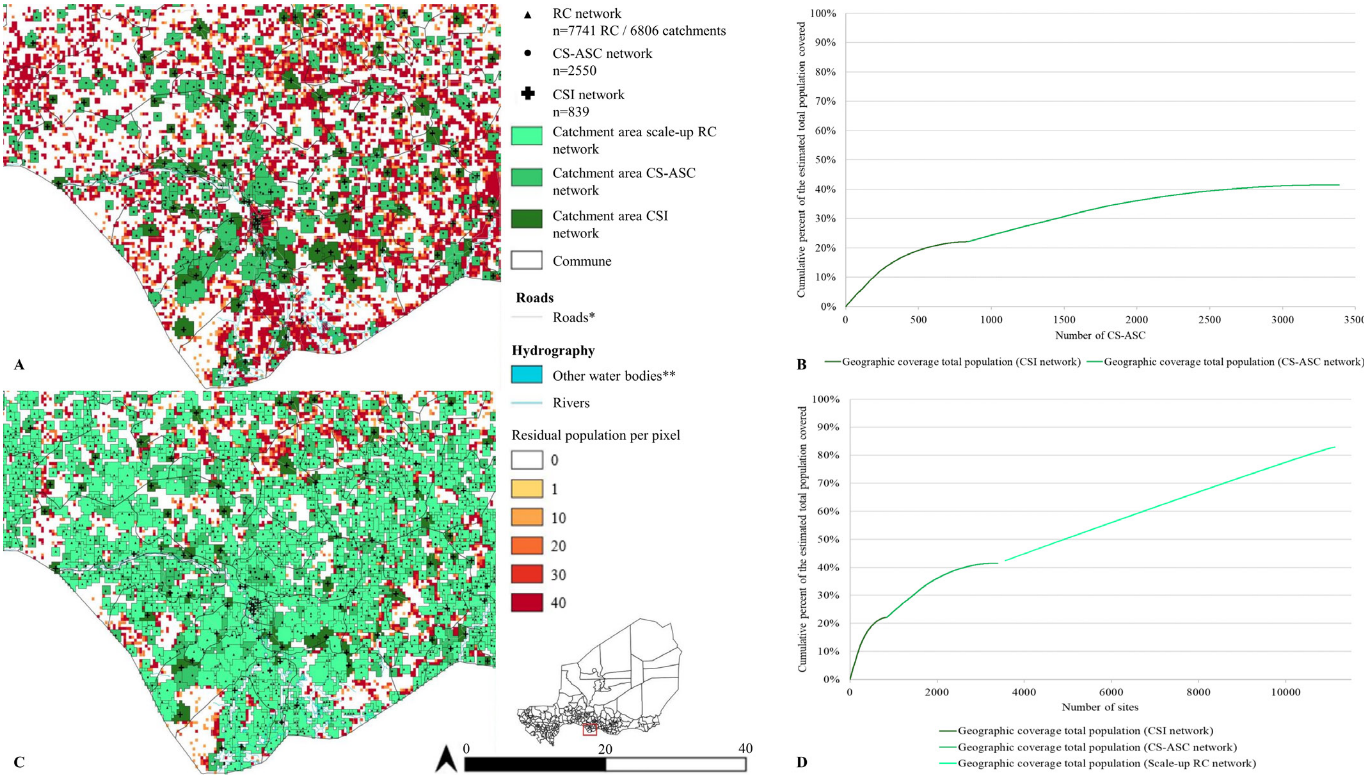


**Figure 3** A) Geographic coverage at 1km x 1km resolution of the CSI (dark green) and CS-ASC networks (medium green) in 2013, 60-minute catchment (walking scenario), with inset near Madarounfa commune in Maradi region; B) Cumulative percent of the estimated total population covered within a 60-minute catchment, walking scenario (y-axis) by the number of CSI (x-axis, dark green line) and CS-ASC (x-axis, medium green line) at 1km x 1km resolution. C) Geographic coverage at 1km x 1km resolution of the CSI network (dark green), CS-ASC (medium green) and hypothetical scale-up RC network (light green) deployed to optimize geographic coverage of the residual population beyond the geographic coverage of the existing CSI and CS-ASC networks (60-minute catchment, walking scenario) in 2013, with maximum population capacity of 1000 people per RC, n=7741 RC in 6806 locations, and inset near Madarounfa commune in Maradi region; D) Cumulative percent of the estimated total population covered within a 60-minute catchment, walking scenario (y-axis) by the number of CSI (x-axis, dark green), CS-ASC (x-axis, medium green), and hypothetical scale-up RC network (x-axis, light green) at 1km x 1km resolution. The hypothetical scale-up RC network targeted 1km x 1km grid cells with at least 250 people situated beyond the geographic coverage of the existing CSI and CS-ASC networks (60-minute catchment, walking scenario) in 2013. Maximum population capacity was set to 1000 people per RC. CSI, Centre de santé intégrée*;* CS-ASC, Case de santé and Agent de santé communautaire; RC, Relais communautaire.

in 2013 (figure 3 and online supplemental appendix 6, tab 'Summary'). Geographical coverage of the estimated total population would increase from 41.5% covered by the existing CSI and CS-ASC networks to 82.9% by the combined CSI, CS-ASC and hypothetical RC networks in 2013 (online supplemental appendix 4, tab 'Summary').

### Efficiency of geographical targeting

Geographical coverage of the estimated residual population beyond the geographical coverage of the existing CSI network was 37.0% by the hypothetical CS-ASC network compared with 25.8% by the existing CS-ASC network, covering an estimated 1.5 million additional people—a 43.6% gain in efficiency (figure 4 and online supplemental appendix 5, tab 'Comparison_Population'). Notably, over one-third (830) of the existing CS-ASC realised less than 30% of their maximum population capacity, indicating redundancy stemming from suboptimal geographical targeting (online supplemental appendix 5, tab 'rPop13_Existing'). Geographical coverage of the estimated residual under-5 deaths beyond the geographical coverage of the existing CSI network was 50.3% by the hypothetical CS-ASC network compared with 34.2% by the existing CS-ASC network, covering an estimated 11 900 under-5 deaths not otherwise covered—a 47.1% gain in efficiency (figure 4 and online supplemental appendix 5, tab 'Comparison_U5deaths'). Geographical coverage of the estimated residual *Pf* malaria cases (all ages) beyond the geographical coverage of the existing CSI network was 50.2% by the hypothetical CS-ASC network compared with 38.0% by the existing CS-ASC network, covering an estimated 737 000 *Pf* malaria cases not otherwise covered—a 32.3% gain in efficiency (figure 4 and online supplemental appendix 5, tab 'Comparison_Malaria'). Our uncertainty analysis for the efficiency of geographical targeting indicates bins/groups of CS-ASC catchments with relatively higher efficiency of geographical targeting could be distinguished from bins/groups of CS-ASC catchments with relatively lower efficiency of

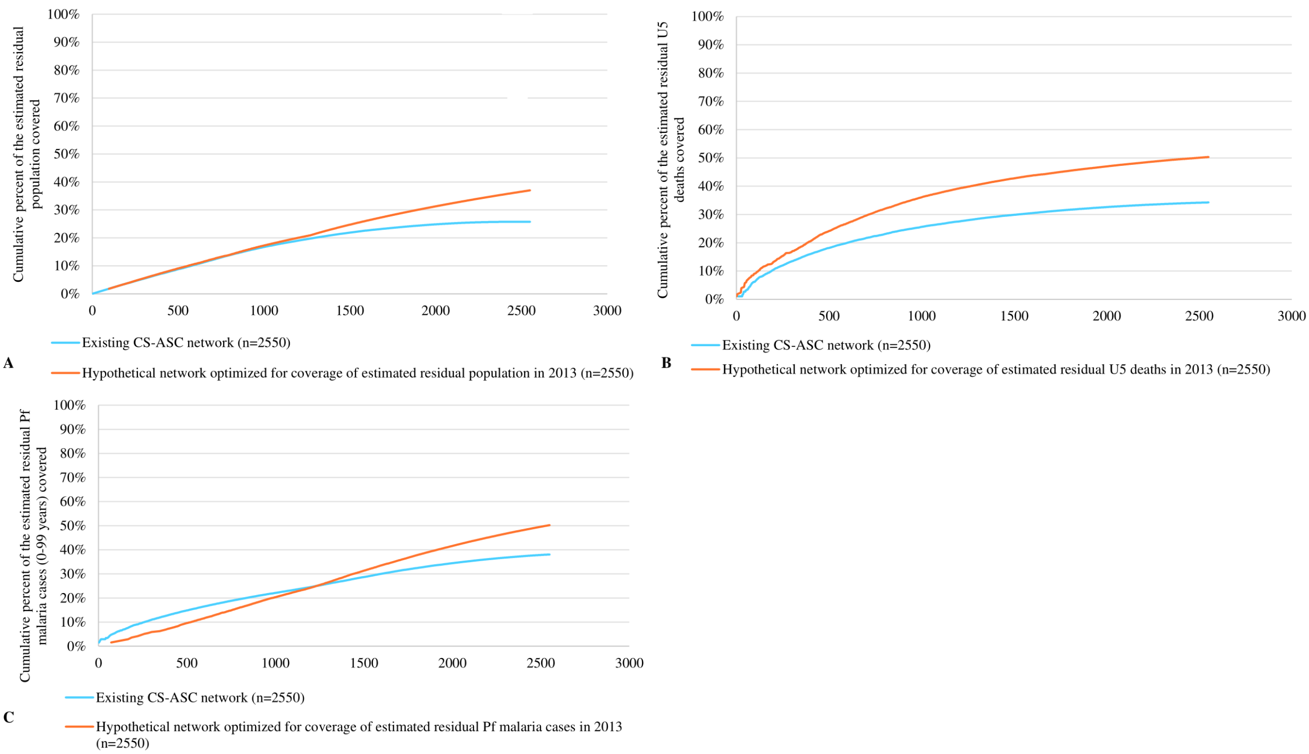


**Figure 4** Targeting of the existing CS-ASC network compared to hypothetical optimized networks at 1km x 1km resolution. A) Comparison of the percent of the estimated residual population beyond the geographic coverage of the existing CSI network (60-minute catchment, walking scenario) that was covered by the existing CS-ASC network compared to a hypothetical CS-ASC network deployed to optimize geographic coverage of the estimated residual population; B) Comparison of the percent of the estimated residual under-five deaths beyond the geographic coverage of the existing CSI network (60-minute catchment, walking scenario) that was covered by the existing CS-ASC network compared to a hypothetical CS-ASC network deployed to optimize geographic coverage of the estimated residual under-five deaths; C) Comparison of the percent of the estimated residual *Pf* malaria cases among all ages (0-99 years) beyond the geographic coverage of the existing CSI network (60-minute catchment, walking scenario) that was covered by the existing CS-ASC network compared to a hypothetical CS-ASC network deployed to optimize geographic coverage of the estimated residual *Pf* malaria cases among all ages (0-99 years). All analyses at 1km x 1km resolution. CS-ASC, Case de santé and Agent de santé communautaire*;* U5, children under five years of age; Pf, Plasmodium falciparum*.*

geographical targeting (online supplemental appendix 6).

## DISCUSSION

### Implications for policy

We understand that rational decisions on targeting and scale-up of community health posts and CHWs, like with health facilities, cannot be addressed purely through modelling, as there are many factors involved in the political economy of health system planning and decision-making that are difficult (or impossible) to capture in models.[32 33] Nonetheless, in our view modelling can provide useful insight for planning and policy decisions. Below we outline key implications of our analysis for policymakers in Niger, as well as other countries of sub-Saharan Africa, with similar contexts and interest in optimising PHC at community level.

First, scale-up of the community health posts (CS) staffed by paid, full-time CHWs (ASC) greatly improved geographical accessibility of PHC services at community level between 2000 and 2013. Other research has indicated that the expansion of PHC at community level may have contributed to improvements in under-5 mortality and other health outcomes[15 16] and still other research has documented the factors that led to the expansion and support for its implementation, including the use of heavily indebted poor countries' funds to finance the construction of the community health posts under the 'special programme' of President Mamadou Tandja, multilateral and bilateral funding to support the monthly payment of CHWs, training and commodities, as well as loans from the World Bank conditional on removal of user fees for children under-5.[32] The experience in Niger with the expansion of the community health posts staffed by paid, full-time CHWs may provide an exemplar model from West Africa from which to learn about scaling up PHC at community level.

Second, our results on the efficiency of geographical targeting of the community health post network imply retargeting of community health posts could result in significant improvements in population coverage and cost-savings that could be reinvested in further scale-up and strengthening of the health system, particularly in the regions of Zinder, Maradi, Tillabéri and Tahoua where over 80% of the uncovered population live. That said, we recognise retargeting community health posts (and thereby resources for CHW) may be disruptive and politically contentious. A less disruptive and perhaps more politically feasible option would be to apply the geographical targeting and scale-up approaches we have described here to optimise further scale-up of the community health post network staffed by paid, full-time CHWs and/or scale the volunteer CHW (RC) network. Compared with the status quo planning process, as evidenced by the inefficiency of the existing community health post network, we would anticipate this optimisation of PHC at community level would result in significant improvements in population coverage and cost-savings that could be reinvested in further scale-up and strengthening of the health system.

Regarding further scale-up of PHC services at community level, there are two additional considerations: first, if choosing between scaling the community health post network of paid, full-time CHWs (ASC) and scaling the volunteer CHW (RC) network, a key consideration is that the scope of work of the RC is more restricted than that of the ASC and the populations covered by the RC would still require geographical accessibility to PHC services that are beyond the remit of the RC but within the scope of the ASC. Depending on the package of PHC services at community level being considered, it may be more efficient and prudent from an equity perspective to optimise the scale-up of the network of community health posts with the paid, full-time CHW and progressively upgrade community health posts to referral facilities (CSI), where needed, to enable broadening of the package of services that are geographically accessible to the population rather than scale up the RC network. Second, in our analysis the scaled up RC network targeted grid cells (100×100 m) with at least 250 population beyond the catchment of the existing referral facility (CSI) and community health post (CS) networks and increased geographical coverage of the population from 41.5% to 82.9%. Covering the remaining 15%–20% of the population would require extending geographical accessibility of PHC services at community level to increasingly small, dispersed communities and will be increasingly less efficient and more logistically challenging than covering the first 80% of the population. Other countries with similar contexts in sub-Saharan Africa are likely to face this challenge. Future analysis and research through collaborative, country-led processes should aim to find optimised, context-specific solutions for covering populations at risk of being left behind.

At the time of writing this manuscript, coauthors were working with the MOPH to update this analysis using datasets from 2020 to 2021. However, we anticipate the insights above will remain valid and useful to planners and policymakers in Niger as they prepare a midterm review of the National Community Health Strategy in 2022, develop an investment case for the GFF and develop a new Health Sector Development Plan for 2024–2028. Planners and policymakers in other countries of sub-Saharan Africa with similar contexts, who are interested in optimising PHC at community level, might also benefit from these insights.

## Limitations

There are important limitations to this study. First, we did not include secondary or tertiary facilities or outreach/mobile sites. We focused on the question of physical access to PHC at community level through community health posts with CHWs and the first level referral health facilities (to which the former refer), rather than secondary or tertiary health facilities and permanent, fixed service locations rather than periodic, mobile services. Several coauthors are currently working with the MOPH on an update to this analysis that will be inclusive of all facility types and CHWs based on data from 2020 to 2021. Second, our analysis is limited by the completeness and quality of the publicly available data on road and river networks. We acknowledge that more complete and/or accurate government or proprietary road and river network data may be available. For the river network, we acknowledge that some rivers, streams and other waterways may not be perennial barriers to movement. We attempted to mitigate this limitation by allowing major road classes (motorway, trunk, primary, secondary and tertiary) to cross rivers/streams and by incorporating data on the hydrographic network from the high-resolution Copernicus land cover layer[21] in our merged land cover layer. We also conducted a sensitivity analysis using only waterways classified as 'rivers' in the rivers input layer as barriers to movement and found this made no important difference to the results (online supplemental appendix 2, tab 'Sensitivity_analysis'). Third, our accessibility coverage, geographical coverage and targeting analyses do not account for uncertainty of the estimates of population. Previous analyses of accessibility coverage and geographical coverage have not uncounted for uncertainty of this kind, but we acknowledge this is an important limitation and area for improving future modelling. Fourth, our analysis does not account for national parks or other 'no–go' zones (eg, military bases) due to lack of access to the geography of these objects for 2013. Fifth, our travel speeds were based on estimated travel speeds used in similar analyses for Niger and other countries in sub-Saharan Africa in the dry season.[7 28] The travel speeds used in our analysis do not account for travel speeds in the rainy season. This choice was justified given that the rainy season spans only 3–4 months of the year and the effects of the rainy season on geographical accessibility are anticipated to be limited in duration (total seasonal rainfall is estimated to result from only 40–50 rain events of which only 2.4%–4.5% are estimated to be extreme rain events) and geographically localised.[34] For these reasons, adjusting the travel speeds to account for the rainy season using a generalised correction factor would be inappropriate.

Adequately adjusting the travel speeds would entail use of empirical data and/or expert knowledge at the local level about the effects of rain events on travel speeds (eg, frequency, duration and location of washed-out bridges, flooding, reductions in travel speeds) which was beyond the scope of the current exercise. Our analysis also does not account for differences in travel speeds by population groups (eg, pregnant women, people with illness and caregivers carrying sick children may walk slower than the general population), river transportation, and our walking plus motorised transportation scenario assumes immediate access to a vehicle once a road is reached and does not account for road traffic or factors impacting road traffic (eg, traffic lights). In addition, we did not attempt to account for uncertainty of the travel speed estimates as some analyses have done using an arbitrary, generalised correction factor of ±20%,[35 36] because in our view it would be better to use empirical data and/or local expert knowledge on this uncertainty and ascertaining such information was beyond the means of the current analysis. Sixth, our analysis does not account for the possibility of accessing health service delivery locations across national boundaries, an important consideration for cross-border and migrant populations. Seventh, the modelled population counts for 2000–2012 use the High Resolution Settlement Layer population settlement footprint from 2015,[25] which may not accurately reflect the population settlement footprint for the early 2000s. Eighth, for our targeting analysis, we resampled the modelled estimates of under-5 mortality rates and *Pf* incidence from 5 km resolution to 1 km resolution due to lack of estimates at 1 km resolution, effectively assuming the values for these parameters at the finer 1 km resolution. However, this limitation is moot given that the aim of the targeting analysis is to optimise the order of cell prioritisation (which potential location for a community health post should be prioritised over another), cell prioritisation is concerned with the relationship between cells (not the absolute value of cells) and the relationship between cells at 5 km resolution was maintained at 1 km resolution. Lastly, the accuracy of the modelled estimates of under-5 mortality rates[26] and *Pf* malaria incidence[27] used in our targeting analysis is unknown. Despite this limitation, results from our uncertainty analysis indicated that our targeting approach could be used to confidently identify bins/groups of health service delivery catchment areas that are relatively more efficient at geographical targeting than other bins/groups—and that this information could be used to optimise geographical targeting of community health posts staffed by CHWs (ASC). An update to this analysis is planned with the MOPH for 2021 and will seek to address the above limitations.

We acknowledge that, in addition to physical accessibility, it is important to consider social and economic barriers to care-seeking (eg, social norms, intrahousehold power dynamics, costs of transportation, opportunity costs of travel time, costs of services and commodities) which may influence access to and use of health services.[37] It is also important to consider the quality of health services and the potential for bypassing.[38 39] Lastly, predominate modes of transportation may vary by socioeconomic status and geography[40] and they may change in response to contextual factors (eg, the lockdowns due to COVID-19 in 2020).

## CONCLUSION

Geographical accessibility of PHC services at community level improved in Niger between 2000 and 2013 through the scale-up of community health posts staffed by paid, full-time CHWs, providing an estimated 2.3 million additional people with physical access to PHC services at community level—including 2.0 million additional people with physical access to iCCM. However, as of 2013, gaps in geographical accessibility remained and efficiency of geographical targeting of community health posts was suboptimal. The approaches to geographical targeting and scale-up described here could be useful for optimising geographical accessibility to PHC services at community level in Niger and similar contexts of sub-Saharan Africa.

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**Contributors** NPO was responsible for the study conceptualisation, methodology, data curation and writing the draft manuscript. OH, IM, KB, AYG, NPO and NR collected data or provided feedback on data. NPO, NR and ZS conducted the formal analysis and were responsible for data visualisation. NPO, NR and TD verified the underlying data. TD, DJ and NR provided supervision and overall guidance. All authors contributed to reviewing and editing the manuscript.

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**Patient consent for publication** Not required.

**Ethics approval** The 2013 georeferenced census of health service delivery networks (CSI, CS and ASC)[19] was conducted by the National Statistics Institute of Niger and the MOPH in the context of management of the public health sector and did not require ethical approval. The protocol for secondary analysis of the 2013 census of CSI, CS and ASC was approved by the Ethics Committee of the University of Western Cape (Registration no: 15/7/271).

**Provenance and peer review** Not commissioned; externally peer reviewed.

**Data availability statement** Data are available in a public, open access repository under the Creative Commons Attribution 4.0 Unported (CC BY 4.0) licence, which permits others to copy, redistribute, remix, transform and build upon this work for any purpose, provided the original work is properly cited, a link to the licence is given, and indication of whether changes were made. See: https://creativecommons.org/licenses/by/4.0/. Supplemental appendices 2–6, videos 1–2, and all model outputs are available in supplemental appendix 1b at https://doi.org/10.5281/zenodo.4428176. All model inputs (except existing service delivery locations) are available in supplemental appendix 1c at https://doi.org/10.6084/m9.figshare.13536779.v6. Health service delivery location data are only available through data sharing agreements with UNICEF and the Ministry of Public Health of Niger.



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**Supplementary Appendix 1**

This file provides supplementary figures, tables, and methods for "Optimising geographical accessibility to primary health care: a geospatial analysis of community health posts and community health workers in Niger" by Nicholas P Oliphant, Nicolas Ray, Khaled Bensaid, Adama Ouedraogo, Asma Yaroh Gali, Oumaru Habi, Ibrahim Maazou, Rocco Panciera, Maria Muñiz, Samuel OM Manda, Zeynabou Sy, Debra Jackson, and Tanya Doherty.

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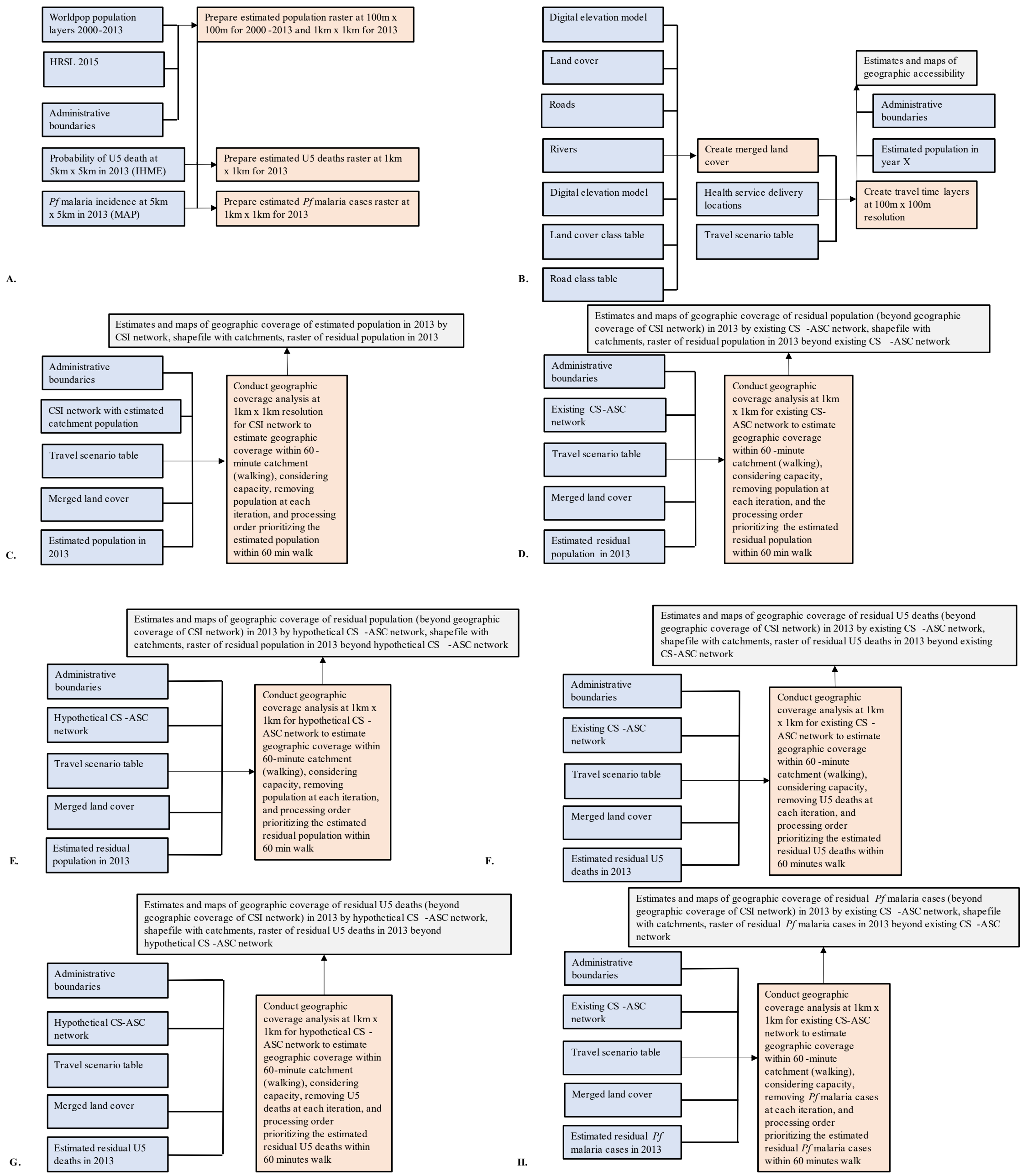
Worldpop population layers 2000-2013
HRSL 2015
Administrative boundaries
Probability of U5 death at 5km x 5km in 2013 (IHME)
*Pf* malaria incidence at 5km x 5km in 2013 (MAP)
Prepare estimated population raster at 100m x 100m for 2000 -2013 and 1km x 1km for 2013
Prepare estimated U5 deaths raster at 1km x 1km for 2013
Prepare estimated *Pf* malaria cases raster at 1km x 1km for 2013
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Roads
Rivers
Digital elevation model
Land cover class table
Road class table
Create merged land cover
Health service delivery locations
Travel scenario table
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B.
Estimates and maps of geographic coverage of estimated population in 2013 by CSI network, shapefile with catchments, raster of residual population in 2013
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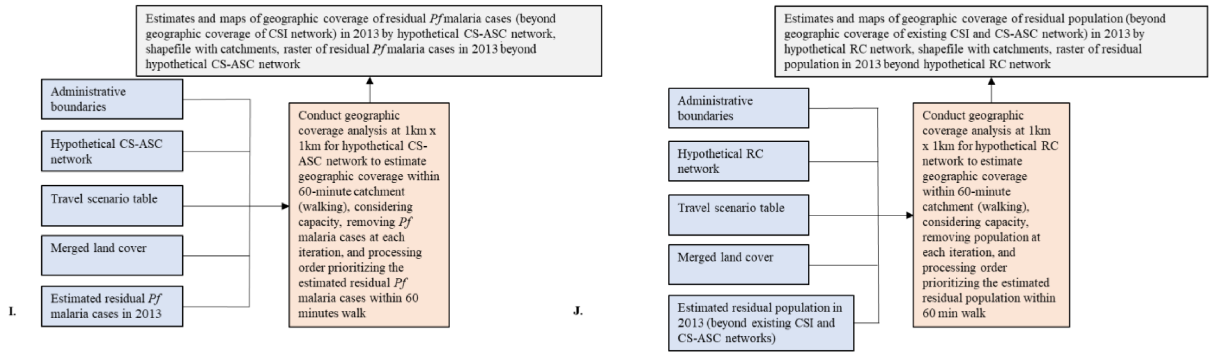
Estimated population in 2013
Conduct geographic coverage analysis at 1km x 1km resolution for CSI network to estimate geographic coverage within 60 -minute catchment (walking), considering capacity, removing population at each iteration, and processing order prioritizing the estimated population within 60 min walk
C.
Estimates and maps of geographic coverage of residual population (beyond geographic coverage of CSI network) in 2013 by existing CS -ASC network, shapefile with catchments, raster of residual population in 2013 beyond existing CS -ASC network
Administrative boundaries
Existing CS-ASC network
Travel scenario table
Merged land cover
Estimated residual population in 2013
Conduct geographic coverage analysis at 1km x 1km for existing CS-ASC network to estimate geographic coverage within 60 -minute catchment (walking), considering capacity, removing population at each iteration, and the processing order prioritizing the estimated residual population within 60 min walk
D.
Estimates and maps of geographic coverage of residual population (beyond geographic coverage of CSI network) in 2013 by hypothetical CS -ASC network, shapefile with catchments, raster of residual population in 2013 beyond hypothetical CS -ASC network
Administrative boundaries
Hypothetical CS -ASC network
Travel scenario table
Merged land cover
Estimated residual population in 2013
Conduct geographic coverage analysis at 1km x 1km for hypothetical CS -ASC network to estimate geographic coverage within 60-minute catchment (walking), considering capacity, removing population at each iteration, and processing order prioritizing the estimated residual population within 60 min walk
E.
Estimates and maps of geographic coverage of residual U5 deaths (beyond geographic coverage of CSI network) in 2013 by existing CS -ASC network, shapefile with catchments, raster of residual U5 deaths in 2013 beyond existing CS-ASC network
Administrative boundaries
Existing CS -ASC network
Travel scenario table
Merged land cover
Estimated residual U5 deaths in 2013
Conduct geographic coverage analysis at 1km x 1km for existing CS -ASC network to estimate geographic coverage within 60 -minute catchment (walking), considering capacity, removing U5 deaths at each iteration, and processing order prioritizing the estimated residual U5 deaths within 60 minutes walk
F.
Estimates and maps of geographic coverage of residual U5 deaths (beyond geographic coverage of CSI network) in 2013 by hypothetical CS -ASC network, shapefile with catchments, raster of residual U5 deaths in 2013 beyond hypothetical CS -ASC network
Administrative boundaries
Hypothetical CS-ASC network
Travel scenario table
Merged land cover
Estimated residual U5 deaths in 2013
Conduct geographic coverage analysis at 1km x 1km for hypothetical CS -ASC network to estimate geographic coverage within 60-minute catchment (walking), considering capacity, removing U5 deaths at each iteration, and processing order prioritizing the estimated residual U5 deaths within 60 minutes walk
G.
Estimates and maps of geographic coverage of residual *Pf* malaria cases (beyond geographic coverage of CSI network) in 2013 by existing CS -ASC network, shapefile with catchments, raster of residual *Pf* malaria cases in 2013 beyond existing CS -ASC network
Administrative boundaries
Existing CS -ASC network
Travel scenario table
Merged land cover
Estimated residual *Pf* malaria cases in 2013
Conduct geographic coverage analysis at 1km x 1km for existing CS-ASC network to estimate geographic coverage within 60 -minute catchment (walking), considering capacity, removing *Pf* malaria cases at each iteration, and processing order prioritizing the estimated residual *Pf* malaria cases within 60 minutes walk
H.




**Supplementary Figure 1. Simplified analysis flow diagram**
(A) Analysis flow for preparation of estimated population layers 2000-2013, estimated U5 deaths layer, and estimated Pf malaria cases layer. (B) Analysis flow for estimates and maps of geographic accessibility. (C) Analysis flow for estimates and maps of geographic coverage of the estimated population in 2013 by the CSI network at 1km x 1km resolution. (D) Analysis flow for estimates and maps of geographic coverage of the estimated residual population in 2013 (beyond the geographic coverage of the CSI network) by the existing CS-ASC network at 1km x 1km resolution. (E) Analysis flow for estimates and maps of geographic coverage of the estimated residual population (beyond geographic coverage of the CSI network) in 2013 by a hypothetical CS-ASC network deployed to optimize geographic coverage of the estimated residual population at 1km x 1km resolution. (F) Analysis flow for estimates and maps of geographic coverage of the estimated residual under-five deaths (beyond geographic coverage of the CSI network) in 2013 by the existing CS-ASC network at 1km x 1km resolution. (G) Analysis flow for estimates and maps of geographic coverage of the estimated residual under-five deaths (beyond geographic coverage of the CSI network) in 2013 by a hypothetical CS-ASC network deployed to optimize geographic coverage of the estimated residual under-five deaths at 1km x 1km resolution. (H) Analysis flow for estimates and maps of geographic coverage of the estimated residual Pf malaria cases (beyond geographic coverage of the CSI network) in 2013 by the existing CS-ASC network deployed to optimize geographic coverage of the estimated residual Pf malaria cases at 1km x 1km resolution. (I) Analysis flow for estimates and maps of geographic coverage of the estimated residual Pf malaria cases (beyond geographic coverage of the CSI network) in 2013 by a hypothetical CS-ASC network deployed to optimize geographic coverage of the estimated residual Pf malaria cases at 1km x 1km resolution. (J) Analysis flow for estimates and maps of geographic coverage of the estimated residual population (beyond geographic coverage of the existing CSI and CS-ASC networks) in 2013 by a hypothetical scaled-up network of RC at 1km x 1km resolution. Blue boxes represent data inputs. Orange boxes represent analysis steps. Grey boxes represent outputs. HRSL = High Resolution Settlement Layer. IHME = Institute for Health Metrics and Evaluation. MAP = Malaria Atlas Project. Pf malaria = Plasmodium falciparum. U5 = children under-five years of age. RC = Relais Communautaire.



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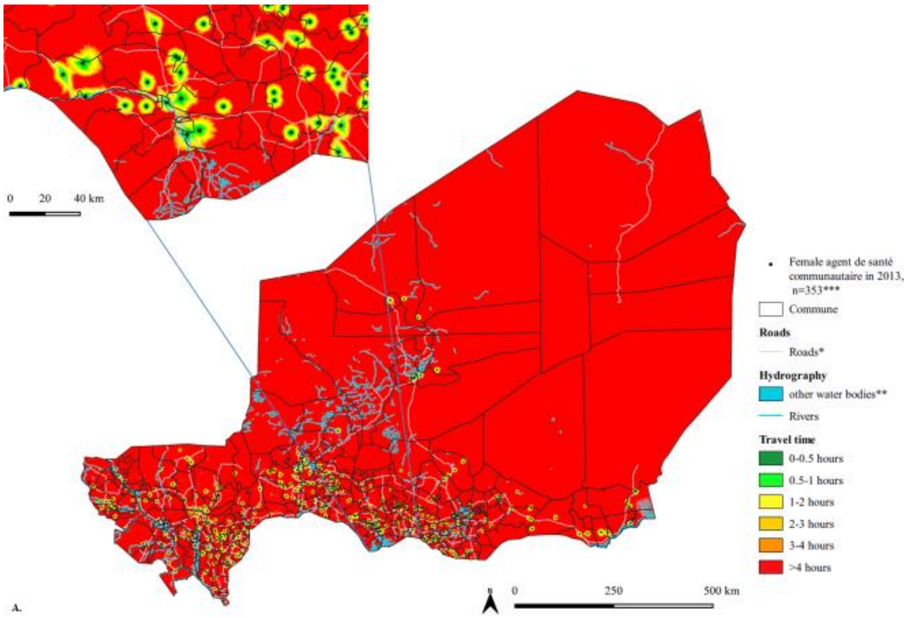
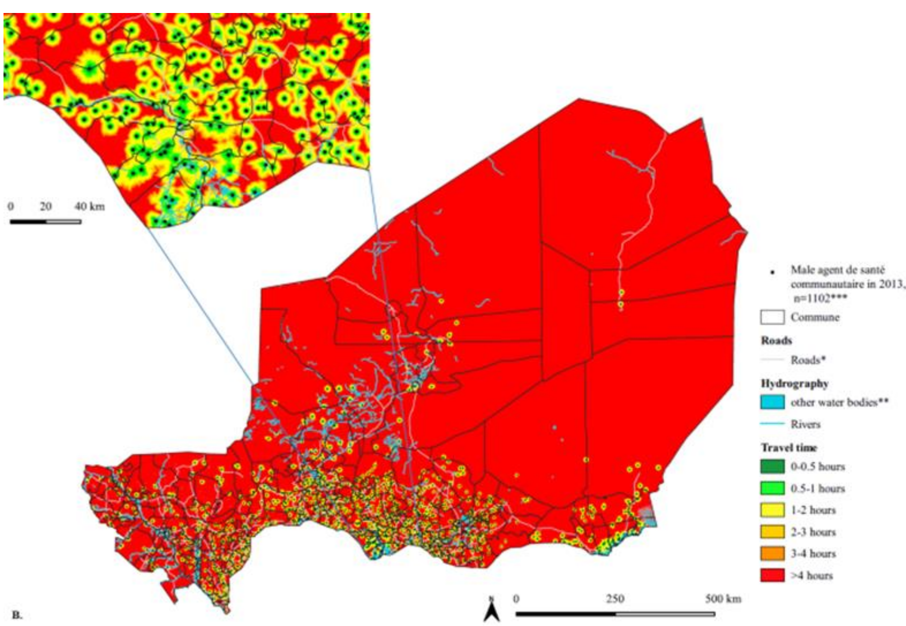
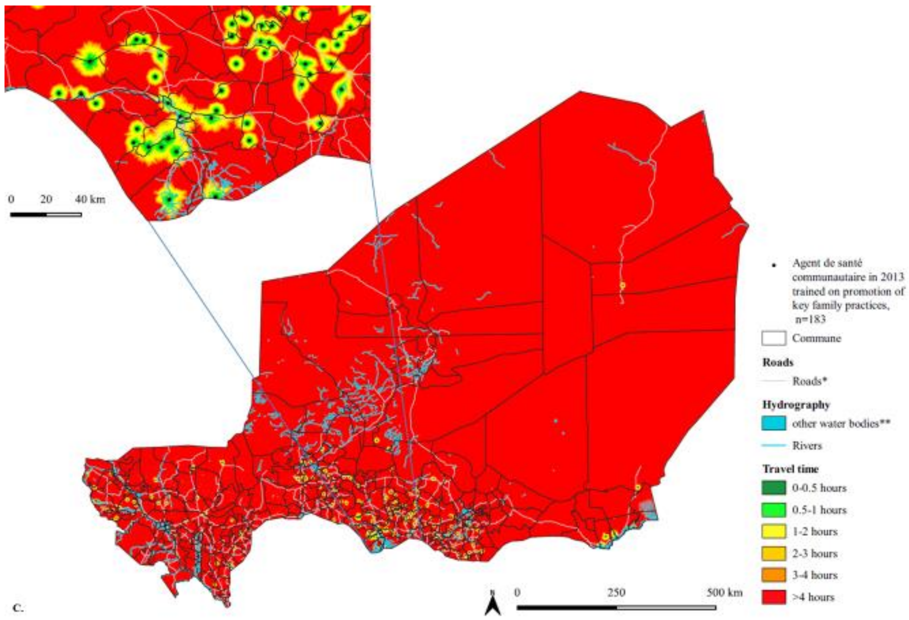



**Supplementary Figure 2 (A). Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest female ASC in 2013 at 100m x 100m resolution.**
Female ASC in 2013, n=353. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands. ***Gender for 2 ASC was not recorded, and these ASC were excluded from the gender analysis.

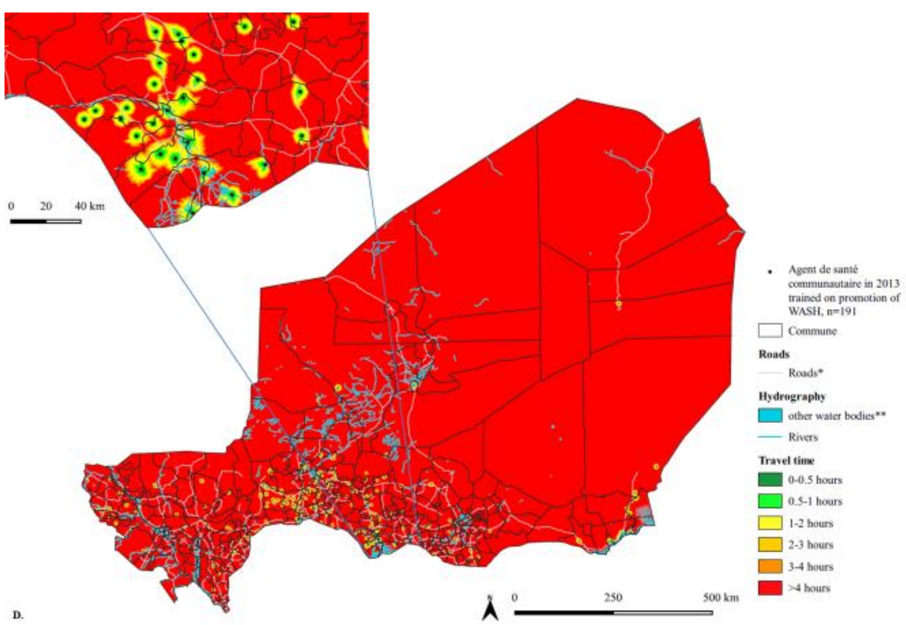



**Supplementary Figure 2 (B). Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest male ASC in 2013 at 100m x 100m resolution.**
Male ASC in 2013, n=1102. *For visualization purposes road classes limited to motorway, trunk, primary,

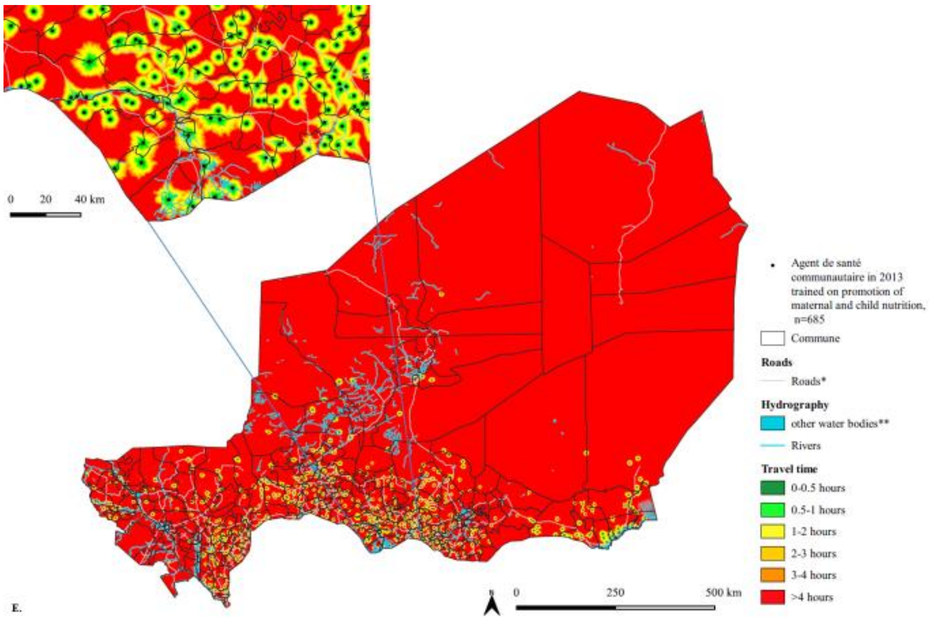
secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands. ***Gender for 2 ASC was not recorded, and these ASC were excluded from the gender analysis.



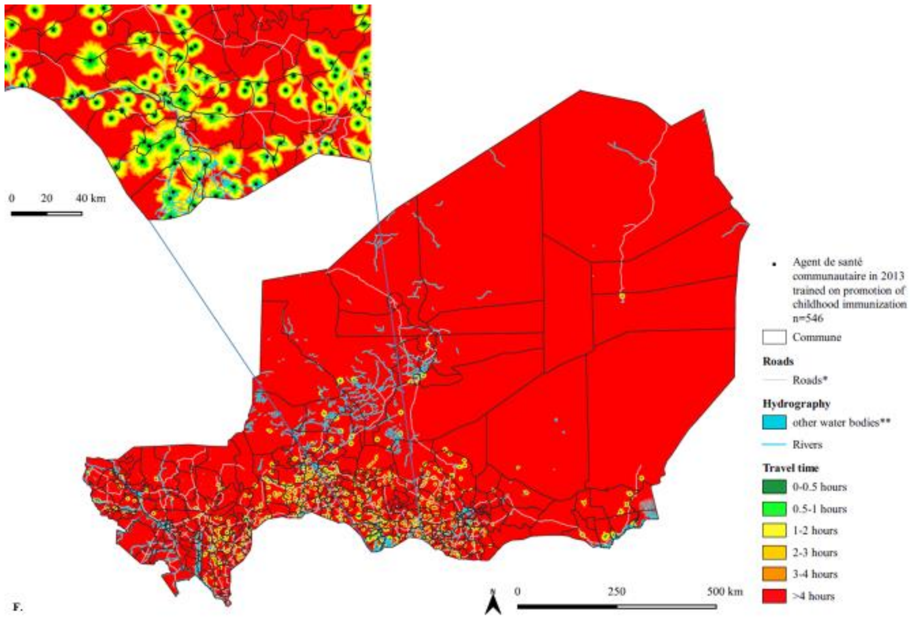

**Supplementary Figure 2 (C). Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest ASC in 2013 trained on promotion of key family practices at 100m x 100m resolution.**
ASC in 2013 trained on promotion of key family practices, n=183; *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary; **other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands



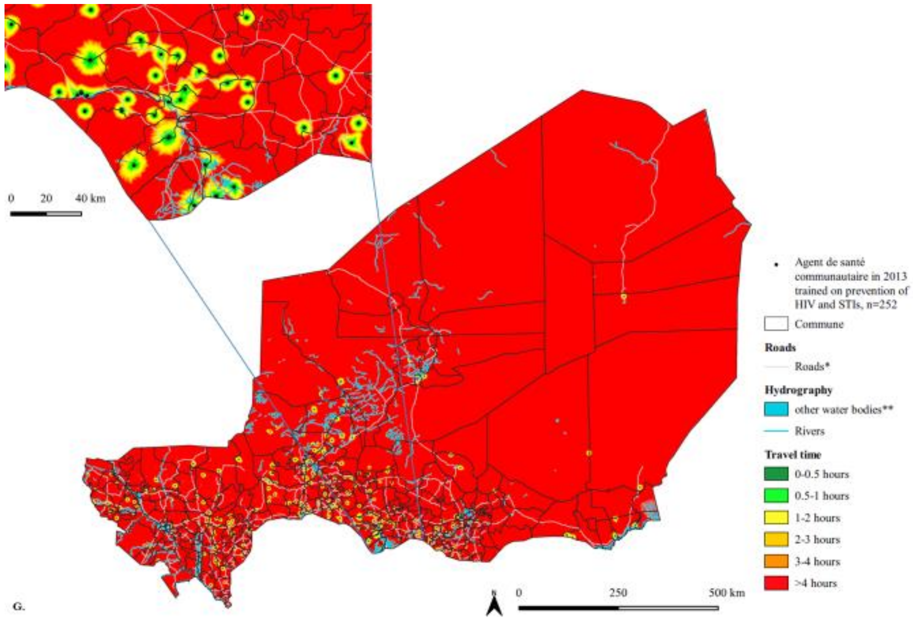
**Supplementary Figure 2 (D). Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest ASC in 2013 trained on promotion of WASH at 100m x 100m resolution.**
ASC in 2013 trained on promotion of WASH, n=1102. ASC=*Agent de santé communautaire*. WASH=water, sanitation, and hygiene. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands




**Supplementary Figure 2 (E). Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest ASC in 2013 trained on promotion of maternal and child nutrition at 100m x 100m resolution.**
ASC in 2013 trained on promotion of maternal and child nutrition, n=685. ASC=*Agent de santé communautaire*. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.

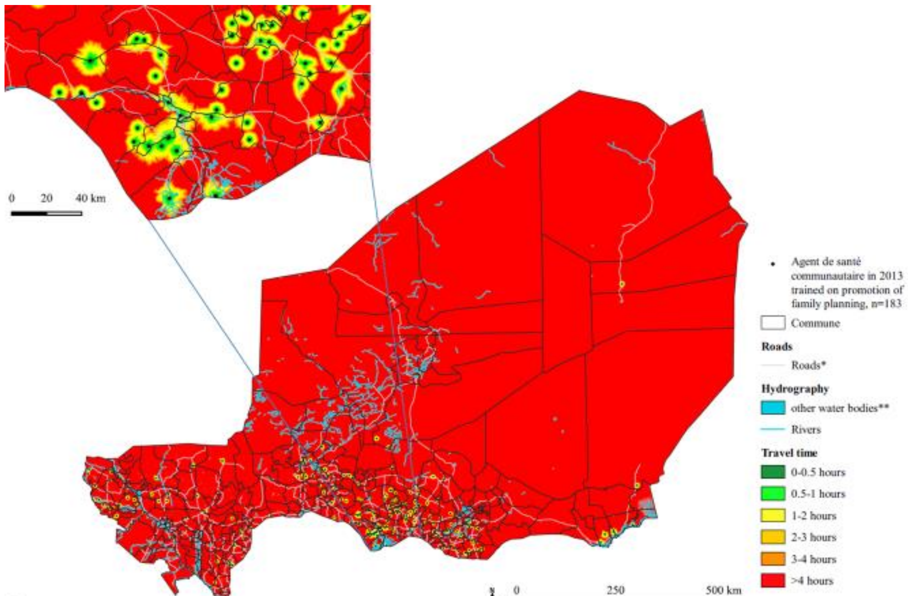



**Supplementary Figure 2 (F). Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest ASC in 2013 trained on promotion of childhood immunization at 100m x 100m resolution.**
ASC in 2013 trained on promotion of childhood immunization, n=546. ASC=*Agent de santé communautaire*. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.



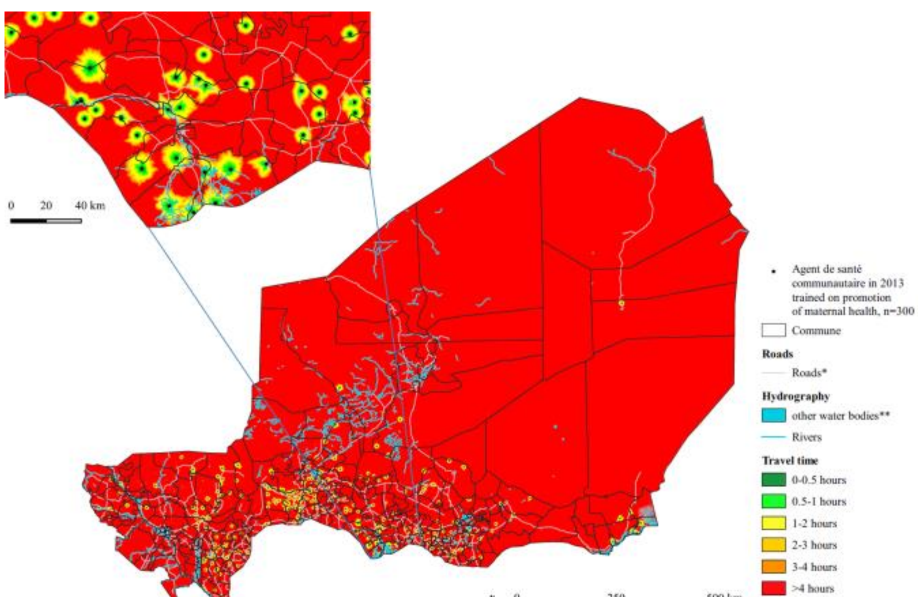

**Supplementary Figure 2 (G). Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest ASC in 2013 trained on prevention of HIV and STI at 100m x 100m resolution.**
ASC in 2013 trained on prevention of HIV and STI, n=252. ASC=*Agent de santé communautaire*. HIV=Human immunodeficiency virus. STI=sexually transmitted infection. *For visualization purposes road classes limited to

motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.



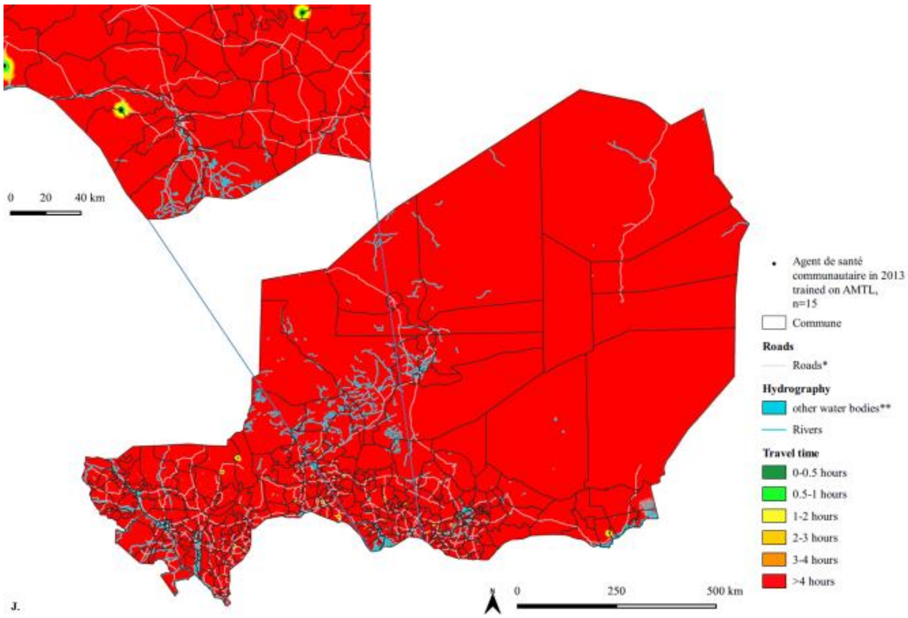

H.

**Supplementary Figure 2 (H). Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest ASC in 2013 trained on family planning at 100m x 100m resolution.**
ASC in 2013 trained on family planning, n=183. ASC=*Agent de santé communautaire*. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.

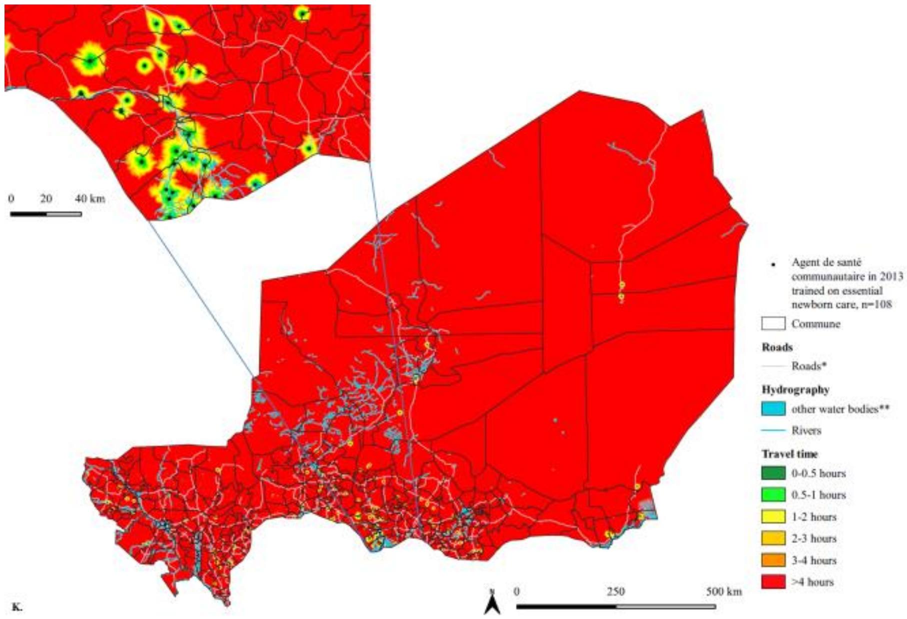



I.

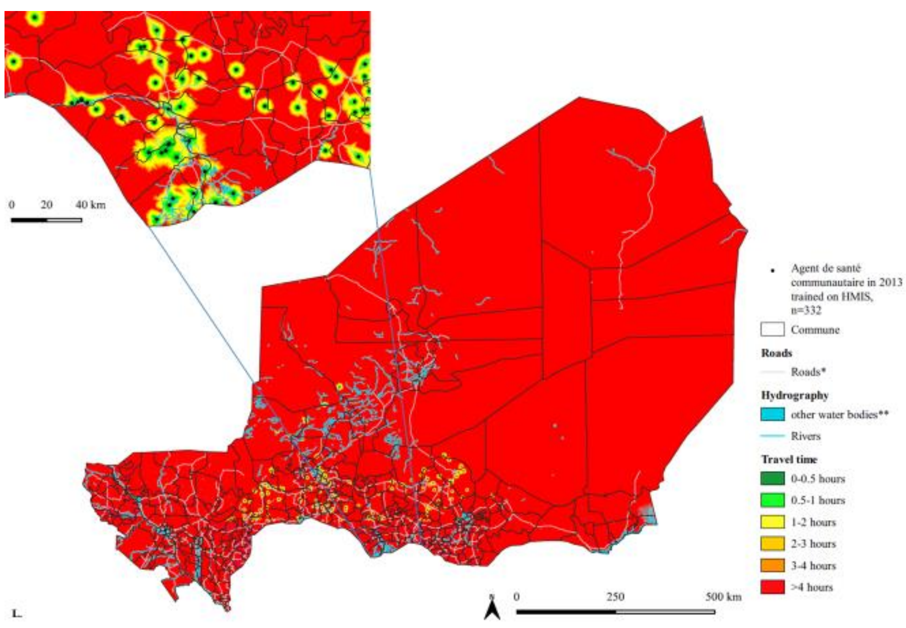
**Supplementary Figure 2 (I). Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest ASC in 2013 trained on promotion of maternal health at 100m x 100m resolution.**
ASC in 2013 trained on promotion of maternal health, n=300. ASC=*Agent de santé communautaire*. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.




**Supplementary Figure 2 (J). Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest ASC in 2013 trained on AMTL at 100m x 100m resolution.**
ASC in 2013 trained on AMTL, n=15. ASC=*Agent de santé communautaire*. AMTL=Active management of the third stage of labor. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.

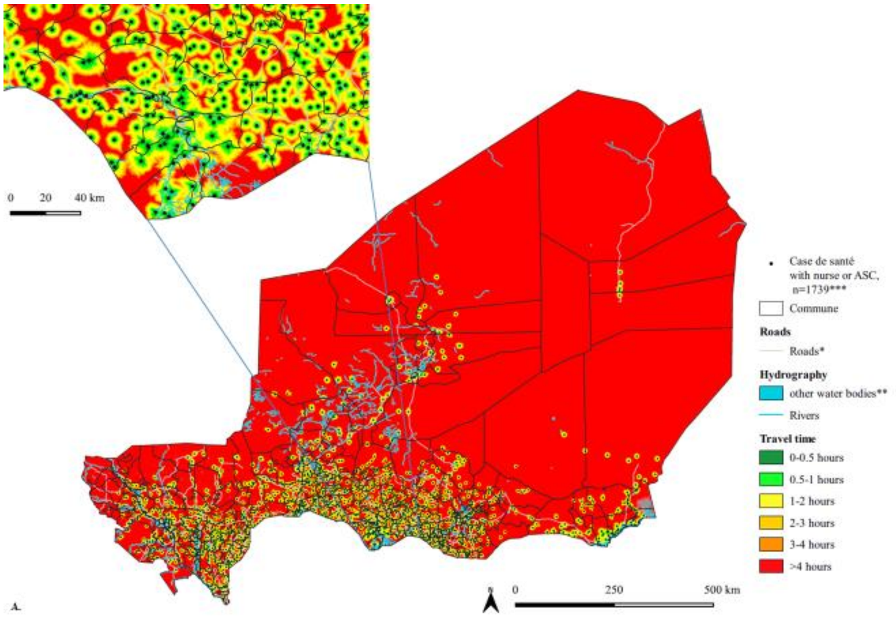



**Supplementary Figure 2 (K). Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest ASC in 2013 trained on essential newborn care at 100m x 100m resolution.**
ASC in 2013 trained on essential newborn care, n=108. ASC=*Agent de santé communautaire*. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.

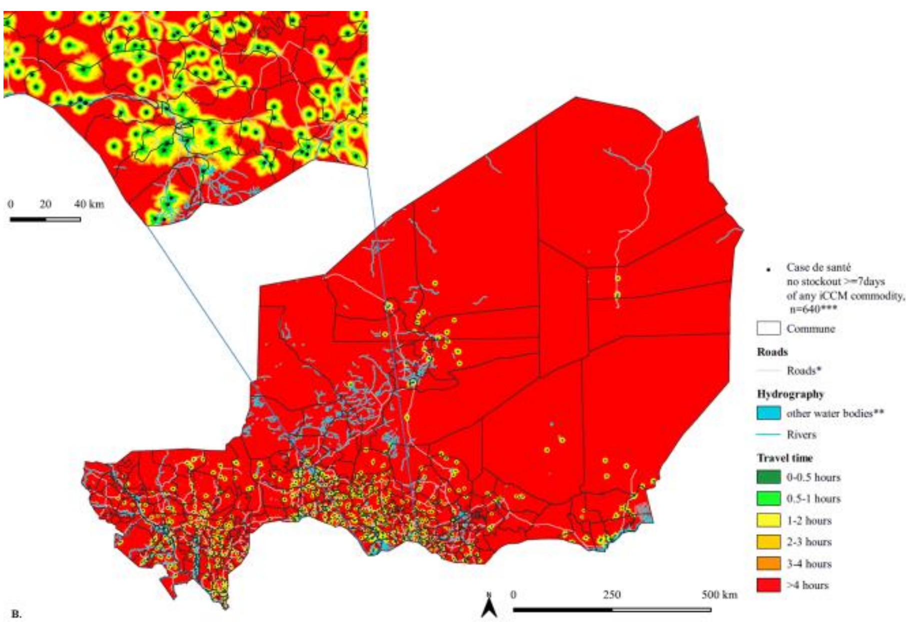



**Supplementary Figure 2 (L). Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest ASC in 2013 trained on the HMIS at 100m x 100m resolution.**
ASC in 2013 trained on the HMIS, n=332. ASC=*Agent de santé communautaire*. HMIS=Health management information system. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and

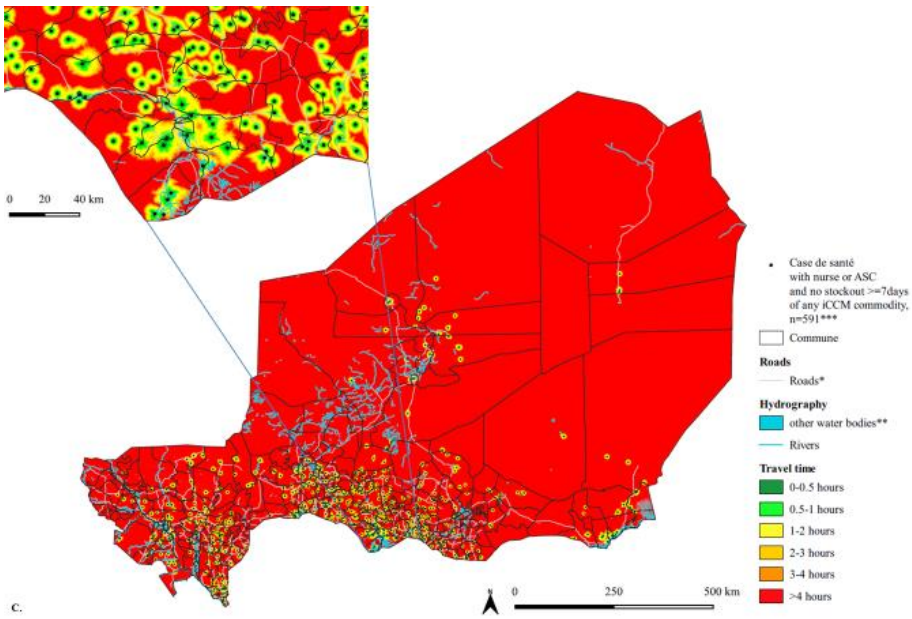
tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.



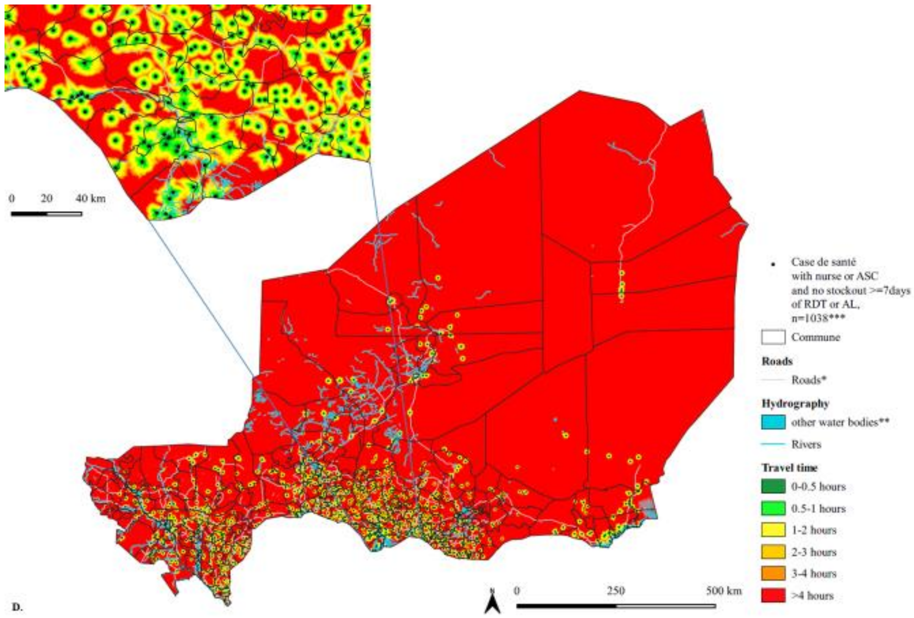

**Supplementary Figure 3 (A). Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest CS in 2013 with a nurse or ASC at 100m x 100m resolution.**
CS in 2013 with a nurse or ASC, n=1739 (***does not include 13 CS that met this criteria but did not have geocoordinates). CS=*Case de santé*. ASC=*Agent de santé communautaire*. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.



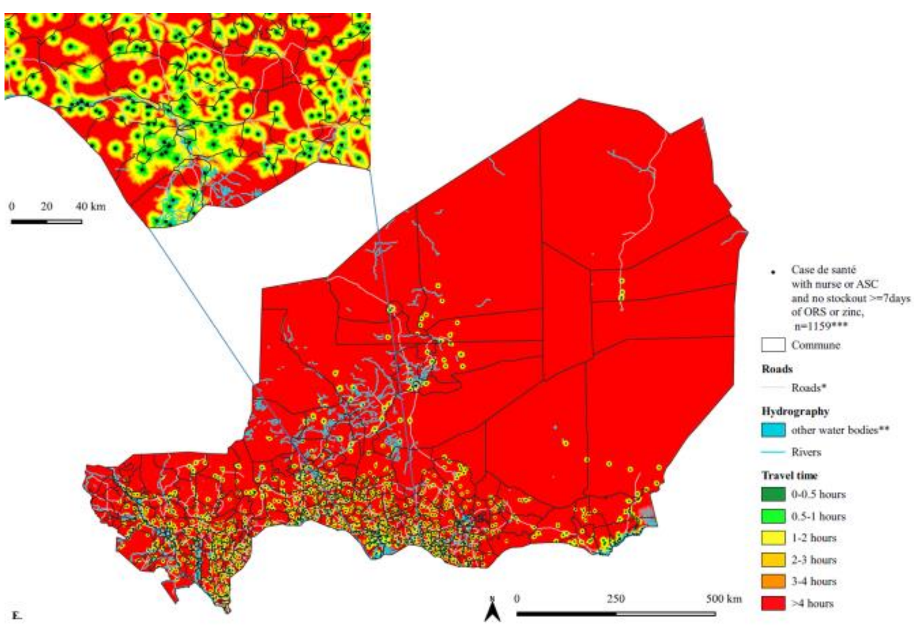
**Supplementary Figure 3 (B). Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest CS in 2013 with no severe stockout of any iCCM commodities at 100m x 100m resolution.**
CS with no stockout of any iCCM commodity lasting longer than seven days, n=640 (***does not include 8 CS that met this criteria but did not have geocoordinates). iCCM commodities = RDT and AL for malaria, low osmolarity ORS and zinc sulfate for diarrhea, cotrimoxazole (pill or syrup) for pneumonia. A stockout of any of these commodities lasting longer than 7 days resulted in the CS being considered as a CS with a severe stockout of any iCCM commodity. CS=*Case de santé*. ASC=*Agent de santé communautaire*. iCCM=integrated community case management. RDT=rapid diagnostic test for malaria. AL=artemether-lumefantrine. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.




**Supplementary Figure 3 (C). Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest CS in 2013 with a nurse or ASC and no severe stockout of any iCCM commodities at 100m x 100m resolution.**
CS in 2013 with a nurse or ASC and no stockout of any iCCM commodity lasting longer than seven days, n=591 (does not include 7 CS that met this criteria but did not have geocoordinates). iCCM commodities = RDT and AL for malaria, low osmolarity ORS and zinc sulfate for diarrhea, cotrimoxazole (pill or syrup) for pneumonia. A stockout of any of these commodities lasting longer than 7 days resulted in the CS being considered as a CS with a severe stockout of any iCCM commodity. CS=*Case de santé*. ASC=*Agent de santé communautaire*. iCCM=integrated community case management. RDT=rapid diagnostic test for malaria. AL=artemether-lumefantrine. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.

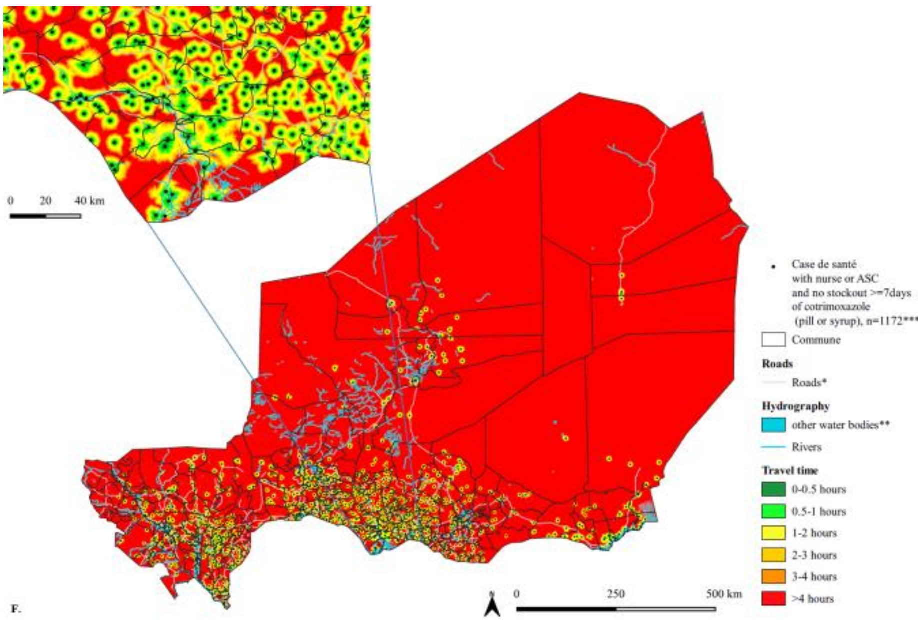



**Supplementary Figure 3 (D). Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest CS in 2013 with a nurse or ASC and no severe stockout of RDT or AL at 100m x 100m resolution.** CS in 2013 with a nurse or ASC and no stockout of RDT or AL lasting longer than seven days, n=1038 (does not include 11 CS that met this criteria but did not have geocoordinates). A stockout of >= 7 days was considered a severe stockout. CS=*Case de santé*. ASC=*Agent de santé communautaire*. RDT=rapid diagnostic test for malaria. AL=artemether-lumefantrine. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.



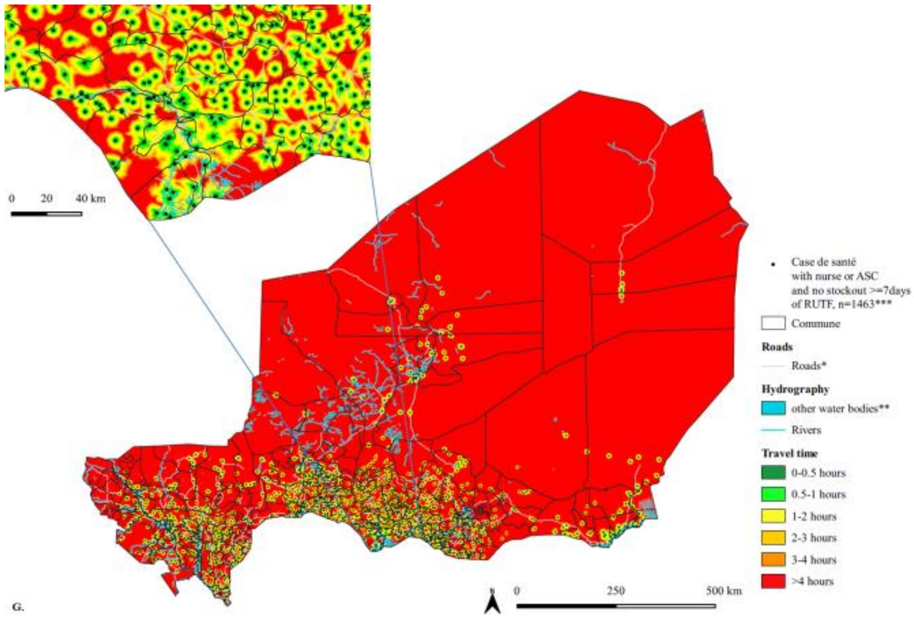
**Supplementary Figure 3 (E). Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest CS in 2013 with a nurse or ASC and no severe stockout of ORS or zinc at 100m x 100m resolution.**

CS in 2013 with a nurse or ASC and no stockout of ORS or zinc lasting longer than seven days, n=1159 (does not include 9 CS that met this criteria but did not have geocoordinates). A stockout of >= 7 days was considered a severe stockout. CS=*Case de santé*. ASC=*Agent de santé communautaire*. ORS = low osmolarity oral rehydration solution. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.

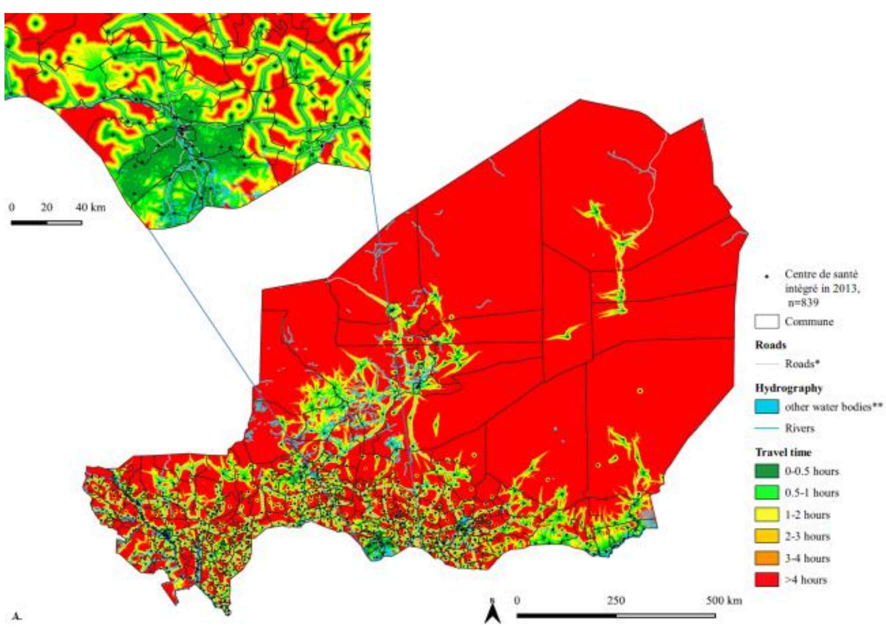



**Supplementary Figure 3 (F). Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest CS in 2013 with a nurse or ASC and no severe stockout of cotrimoxazole at 100m x 100m resolution.**

CS in 2013 with a nurse or ASC and no stockout of cotrimoxazole (pill or syrup) lasting longer than seven days, n=1172 (does not include 7 CS that met this criteria but did not have geocoordinates). A stockout of >= 7 days was considered a severe stockout. CS=*Case de santé*. ASC=*Agent de santé communautaire*. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.

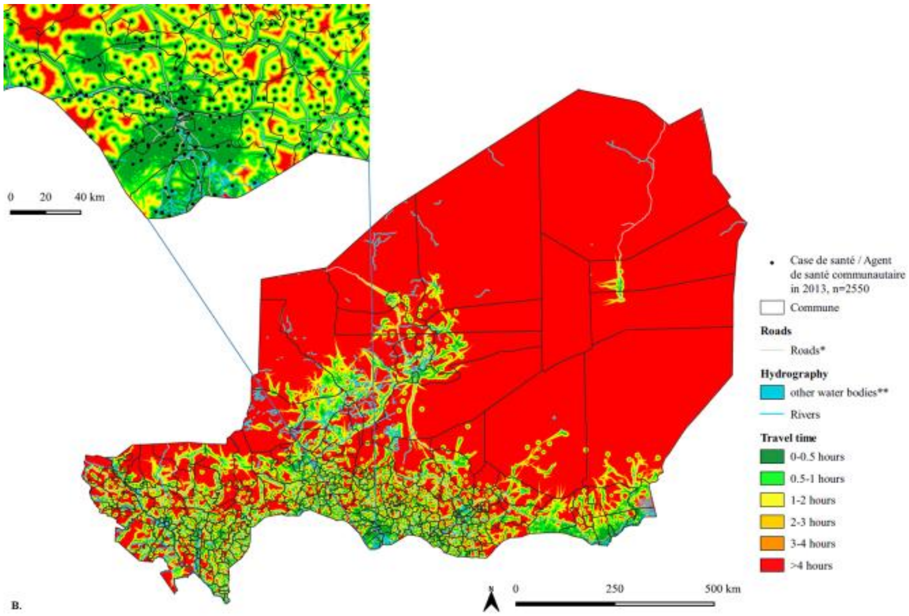



**Supplementary Figure 3 (G). Geographic accessibility (travel time in minutes, walking in dry conditions) to the nearest CS in 2013 with a nurse or ASC and no severe stockout of RUTF at 100m x 100m resolution.** CS in 2013 with a nurse or ASC and no stockout of RUTF lasting longer than seven days, n=1463 (does not include 9 CS that met this criteria but did not have geocoordinates). A stockout of >= 7 days was considered a severe stockout. CS=*Case de santé*. ASC=*Agent de santé communautaire*. RUTF=ready-to-eat therapeutic food. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.

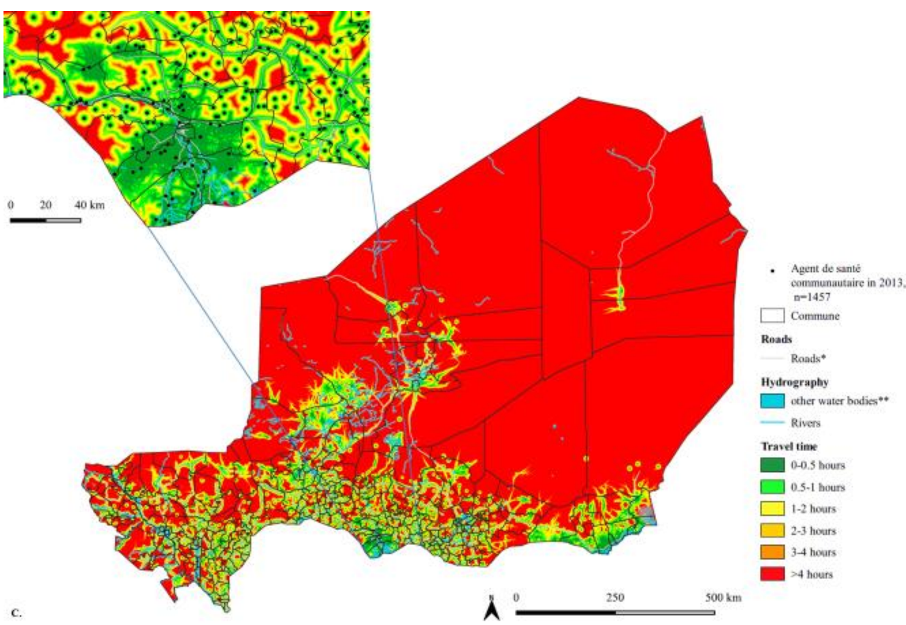



**Supplementary Figure 4. (A) Geographic accessibility (travel time in minutes, walking + motorized transportation in dry conditions) to the nearest CSI in 2013 at 100m x 100m resolution.**

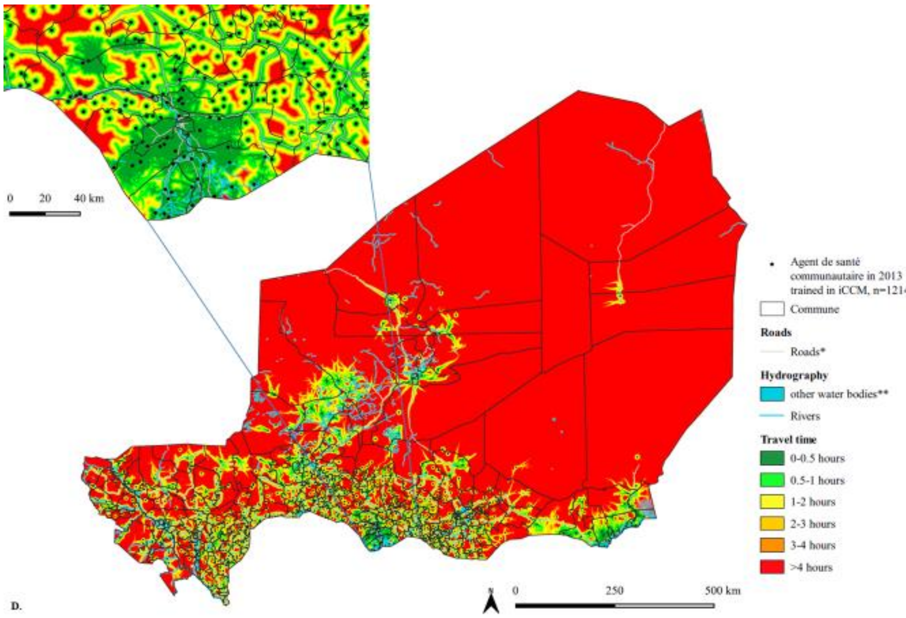
CSI in 2013, n=839. CSI=*Centre de santé intégrée*. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.




**Supplementary Figure 4. (B) Geographic accessibility (travel time in minutes, walking + motorized transportation in dry conditions) to the nearest CS/ASC in 2013 at 100m x 100m resolution.**
CS/ASC in 2013, n=2550. CS/ASC=*Case de santé / Agent de santé communautaire*. ASC=*Agent de santé communautaire*. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.



**Supplementary Figure 4. (C) Geographic accessibility (travel time in minutes, walking + motorized transportation in dry conditions) to the nearest ASC in 2013 at 100m x 100m resolution.**
ASC in 2013, n=1457. ASC=*Agent de santé communautaire*. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.




**Supplementary Figure 4. (D) Geographic accessibility (travel time in minutes, walking + motorized transportation in dry conditions) to the nearest ASC in 2013 trained on iCCM at 100m x 100m resolution.**
ASC in 2013 trained on iCCM, n=1214. ASC=*Agent de santé communautaire*. iCCM=integrated community case management. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.



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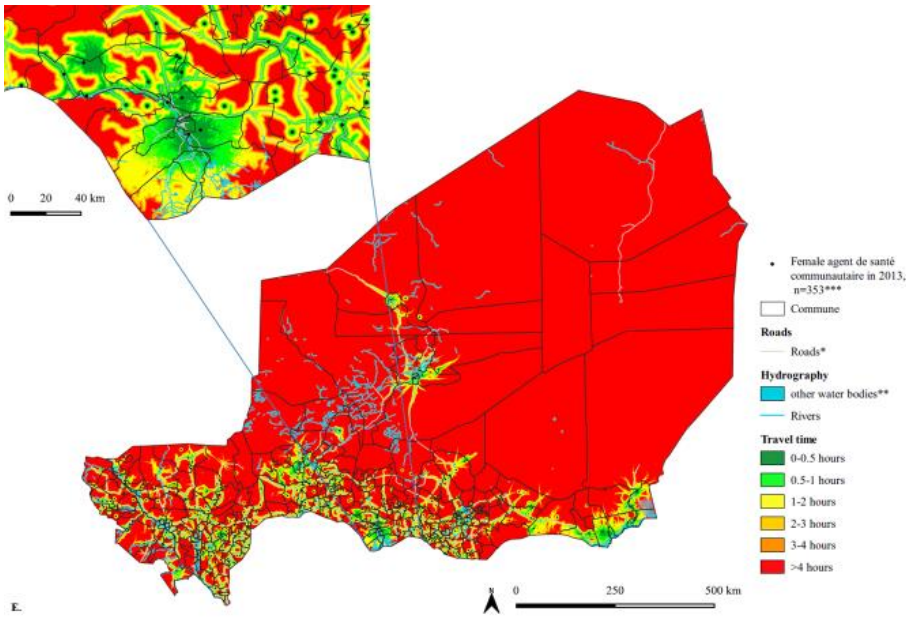
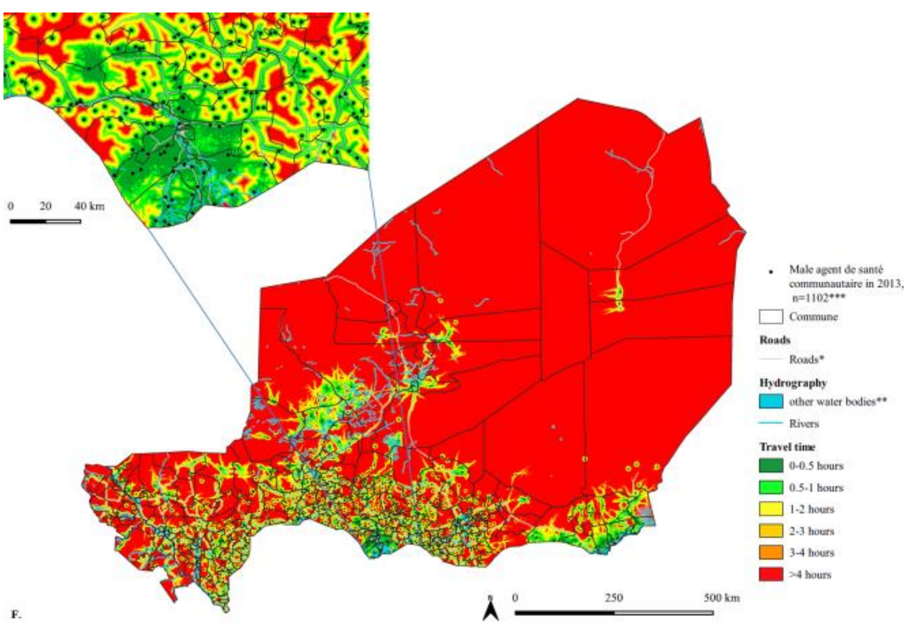
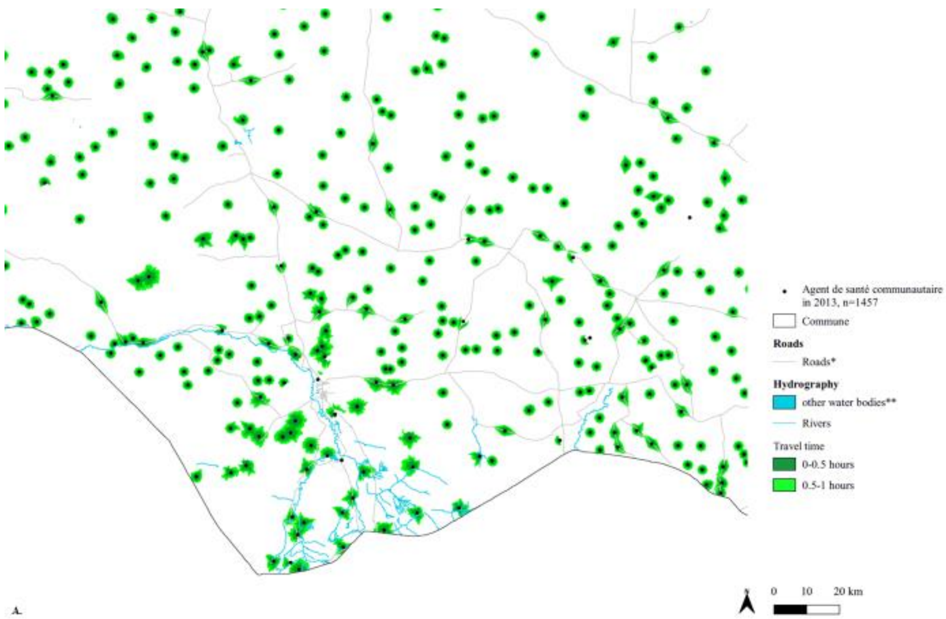



**Supplementary Figure 4. (E) Geographic accessibility (travel time in minutes, walking + motorized transportation in dry conditions) to the nearest female ASC in 2013 at 100m x 100m resolution.**
Female ASC in 2013, n=353. ASC=*Agent de santé communautaire*. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands. ***Gender for 2 ASC was not recorded, and these ASC were excluded from the gender analysis.

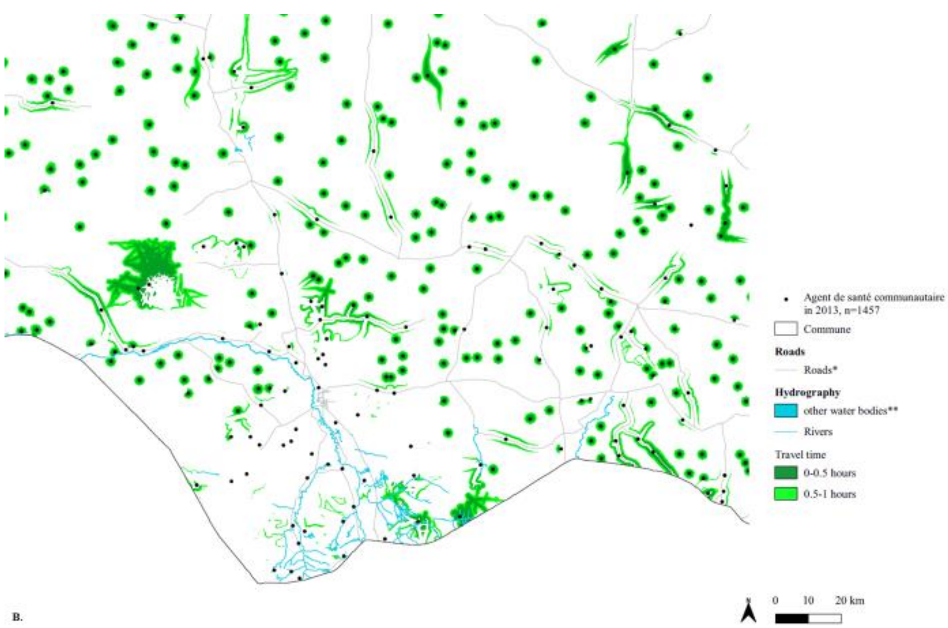



**Supplementary Figure 4. (F) Geographic accessibility (travel time in minutes, walking + motorized transportation in dry conditions) to the nearest male ASC in 2013 at 100m x 100m resolution.**
Male ASC in 2013 trained on iCCM, n=1102. ASC=*Agent de santé communautaire*. *For visualization purposes

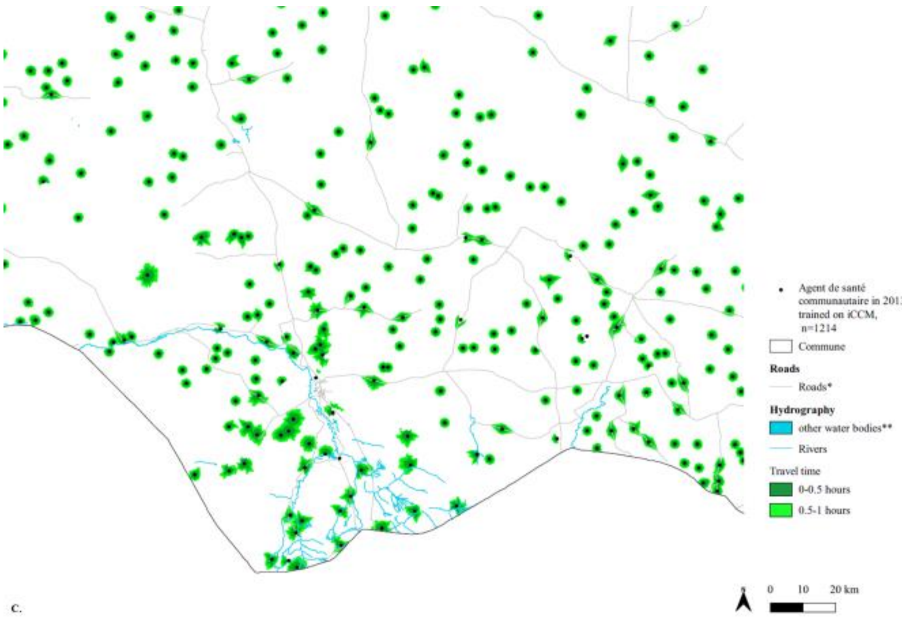
road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands. ***Gender for 2 ASC was not recorded, and these ASC were excluded from the gender analysis.




**Supplementary Figure 5 (A). Contribution of ASC to additional geographic accessibility beyond the existing CSI and CS (without ASC) networks in 2013 (walking scenario) at 100m x 100m resolution.**
ASC in 2013, n=1457, walking scenario. ASC=*Agent de santé communautaire*. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.



**Supplementary Figure 5 (B). Contribution of ASC to additional geographic accessibility beyond the existing CSI and CS (without ASC) networks in 2013 (walking + motorized transportation scenario) at 100m x 100m resolution.**
ASC in 2013, n=1457, walking + motorized transportation scenario. ASC=*Agent de santé communautaire*. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.




c.

**Supplementary Figure 5 (C). Contribution of ASC trained on iCCM to additional geographic accessibility beyond the existing CSI and CS (without ASC) networks in 2013 (walking scenario) at 100m x 100m resolution.**
ASC in 2013 trained on iCCM, n=1214, walking scenario. ASC=*Agent de santé communautaire*. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.



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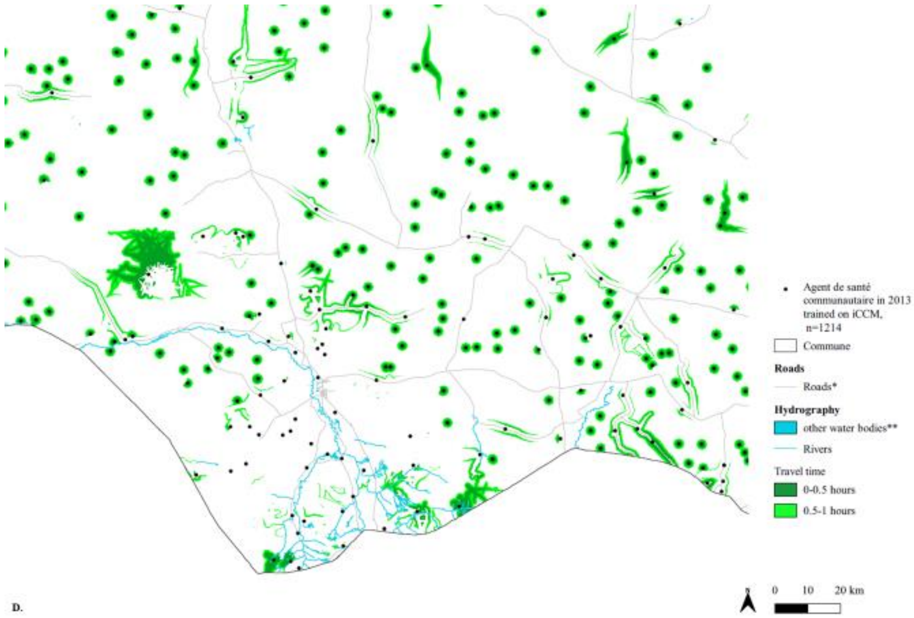
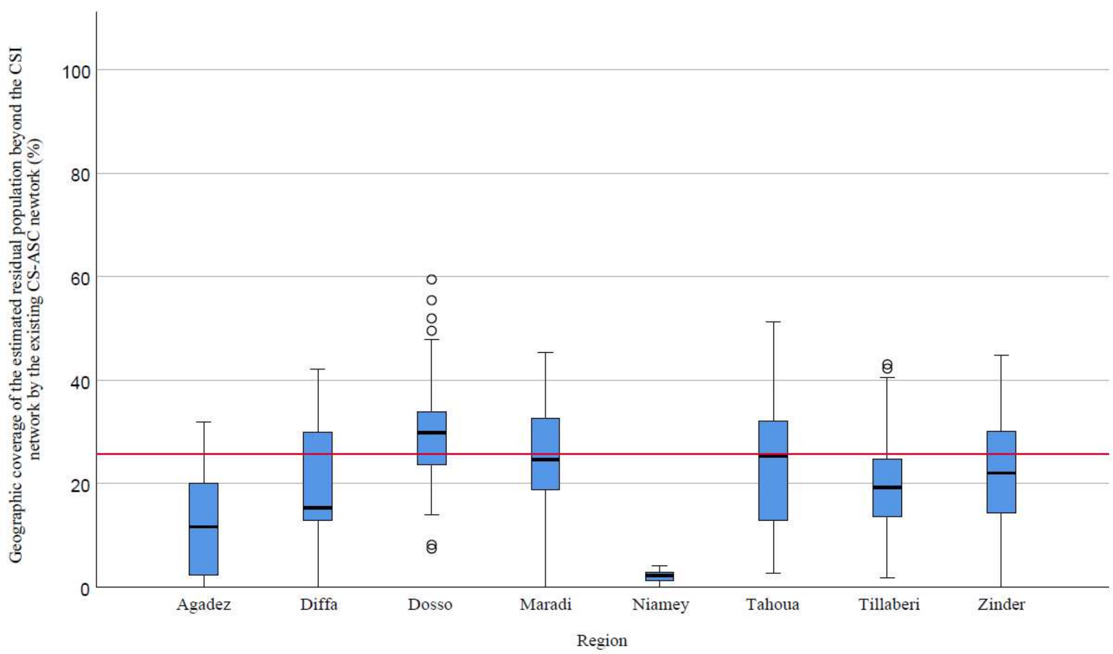
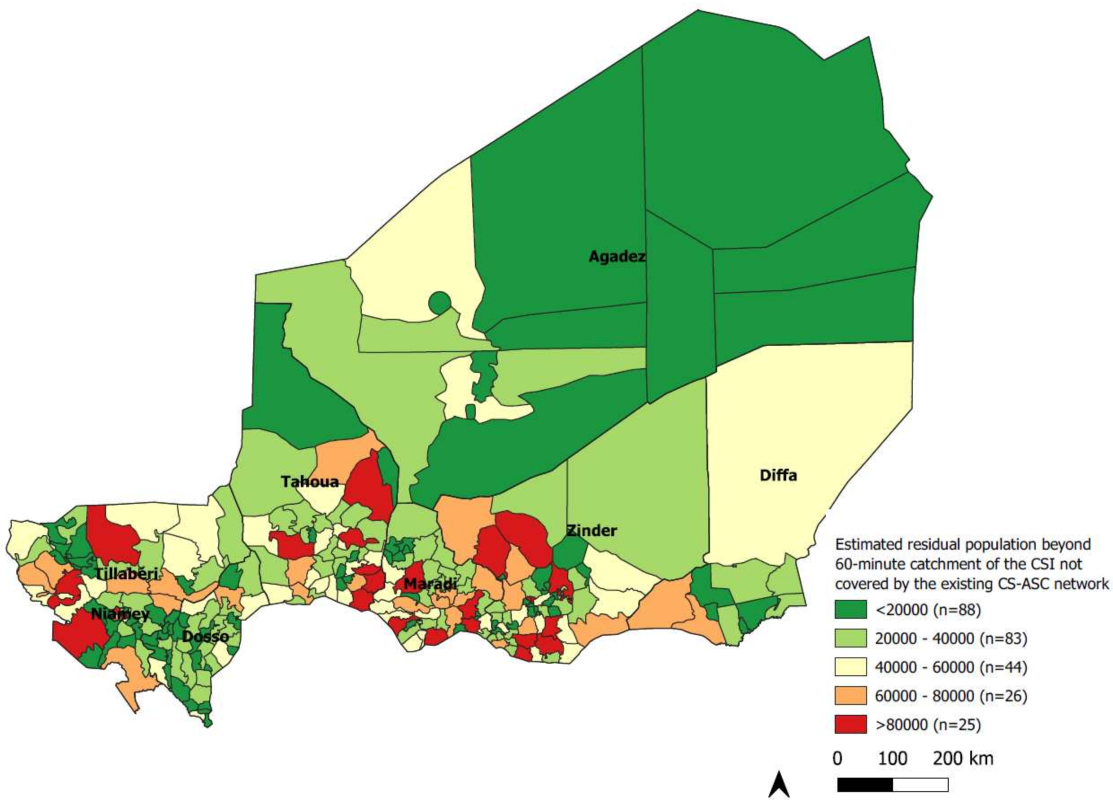



**Supplementary Figure 5 (D). Contribution of ASC trained on iCCM to additional geographic accessibility beyond the existing CSI and CS (without ASC) networks in 2013 (walking + motorized transportation scenario) at 100m x 100m resolution.**

ASC in 2013 trained on iCCM, n=1214, walking + motorized transportation scenario. ASC=*Agent de santé communautaire*. *For visualization purposes road classes limited to motorway, trunk, primary, secondary, and tertiary. **Other water bodies from landcover layer included permanent water bodies, temporary water bodies and herbaceous wetlands.



**Supplementary Figure 6a. Median and interquartile range of geographic coverage at commune level (administrative level 3) of the residual population beyond the geographic coverage of the CSI network that were covered by the existing CS-ASC network, by region (administrative level 1) at 1km x 1km resolution.** Median and interquartile range of geographic coverage at commune level (administrative level 3) of the residual population beyond the geographic coverage (60-minute catchment, walking scenario) of the CSI network that were covered by the existing CS-ASC network (60-minute catchment, walking scenario) by region (administrative level 1). Red line at national geographic coverage of 25.8%.




**Supplementary Figure 6b. Estimated population beyond a 60-minute catchment of the CSI network not covered by the existing CS-ASC network, by commune (administrative level 3).**



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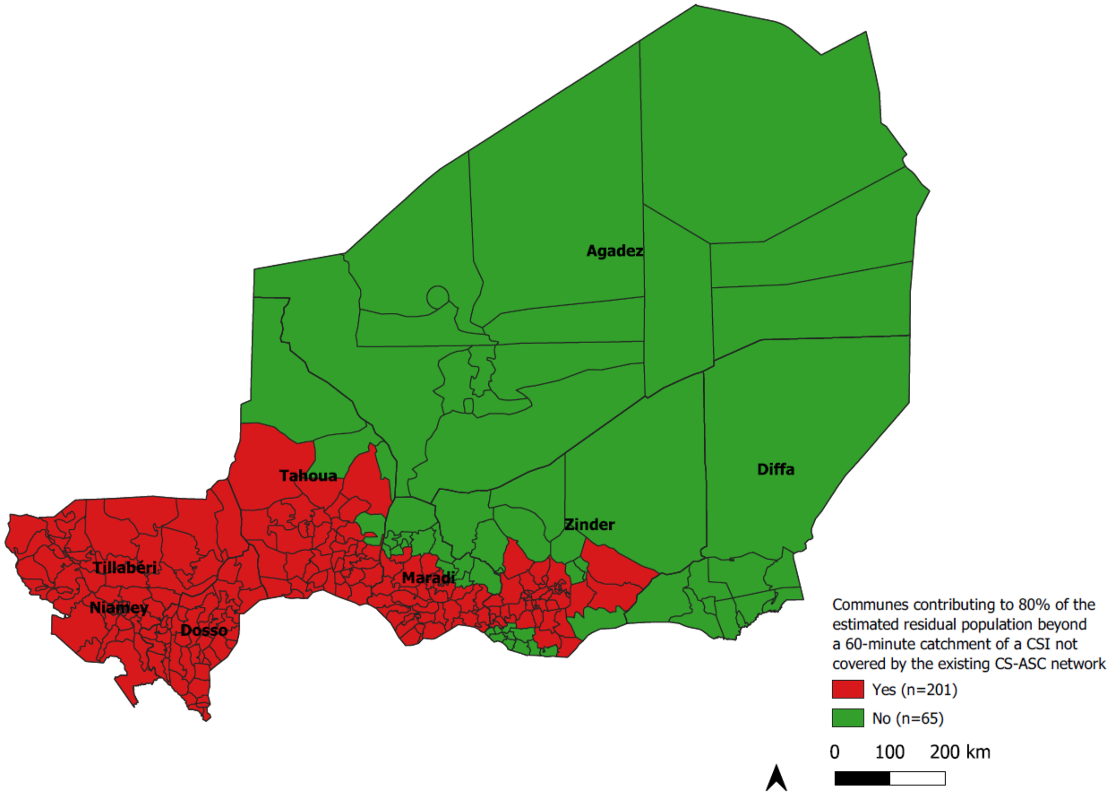
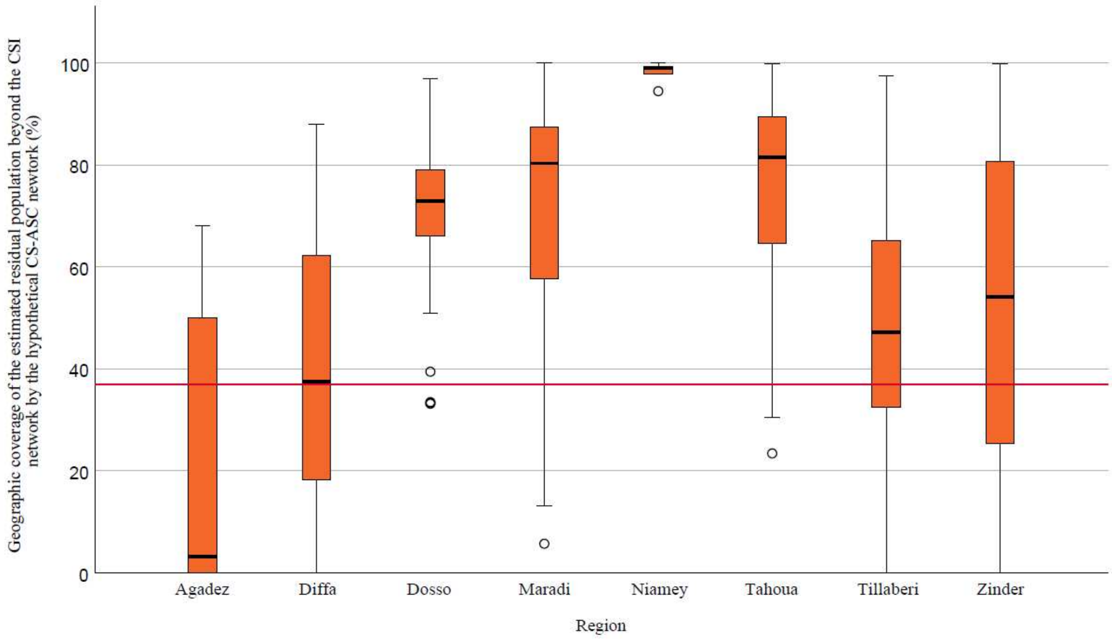
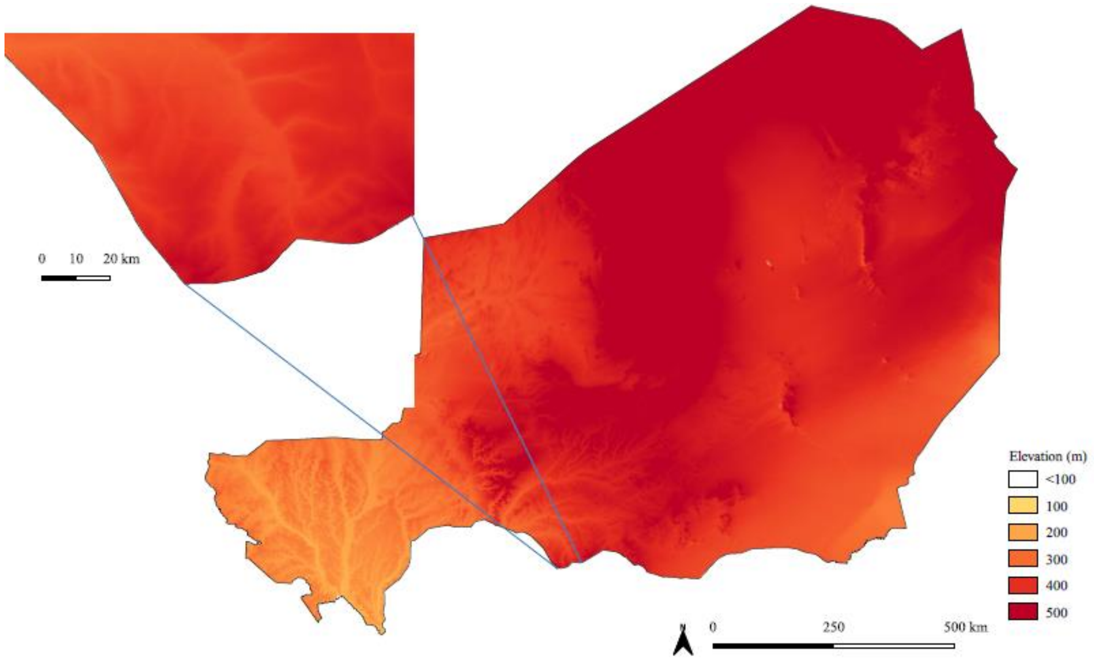


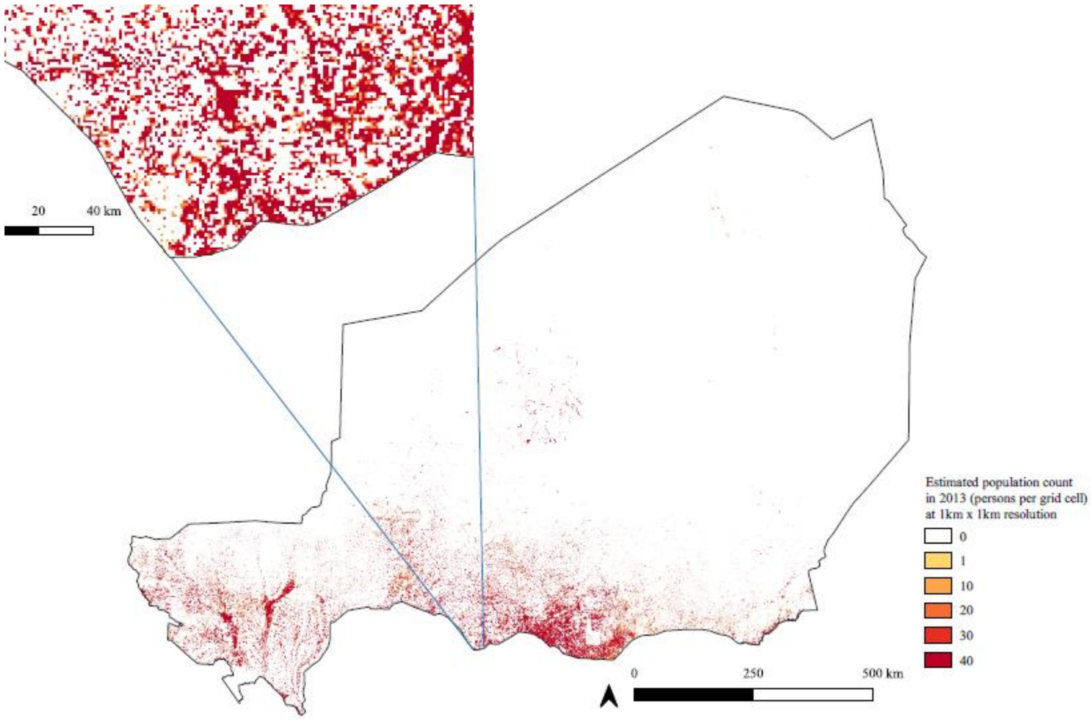

**Supplementary Figure 6c. Communes contributing to 80% of the estimated residual population beyond a 60-minute catchment of the CSI network not covered by the existing CS-ASC network, by commune (administrative level 3).**



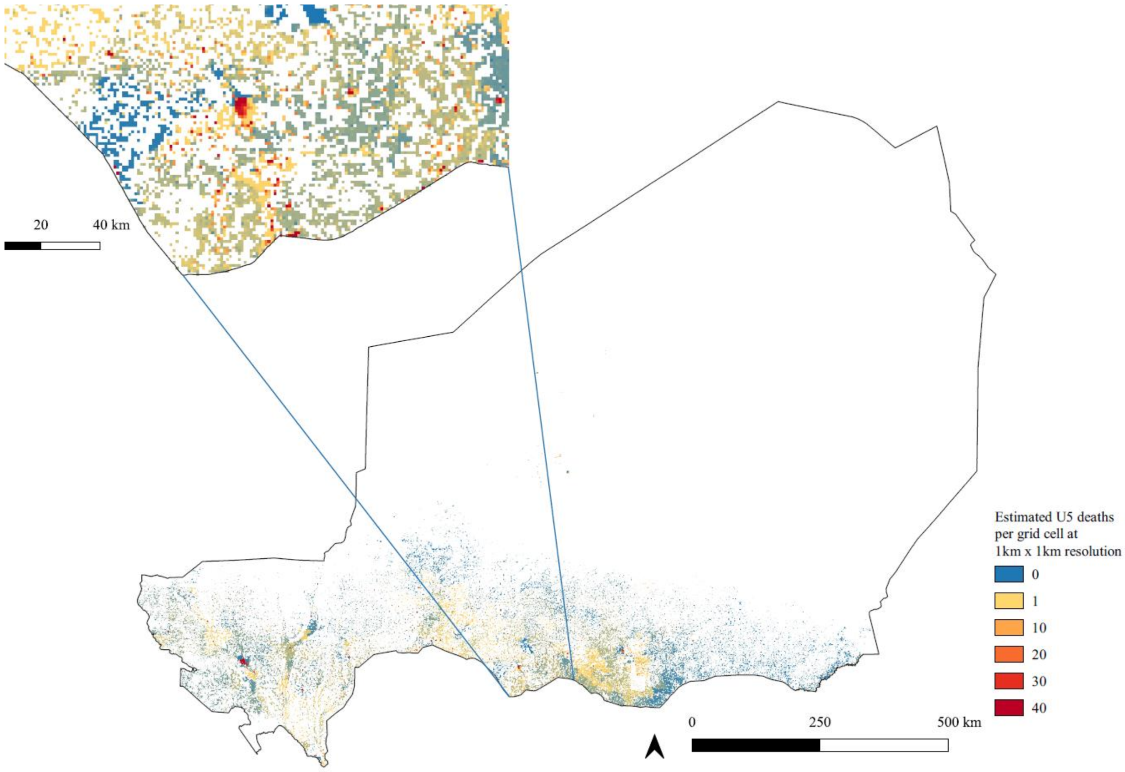

**Supplementary Figure 7. Median and interquartile range of geographic coverage at commune level (administrative level 3) of the residual population beyond the geographic coverage of the CSI network that were covered by the hypothetical CS-ASC network deployed to optimize geographic coverage of the residual population, by region (administrative level 1) at 1km x 1km resolution.**
Median and interquartile range of geographic coverage at commune level (administrative level 3) of the residual population beyond the geographic coverage (60-minute catchment, walking scenario) of the CSI network that were covered by the hypothetical CS-ASC network deployed to optimize geographic coverage of the residual population (60-minute catchment, walking scenario) by region (administrative level 1). Red line at national geographic coverage of 46.8%.



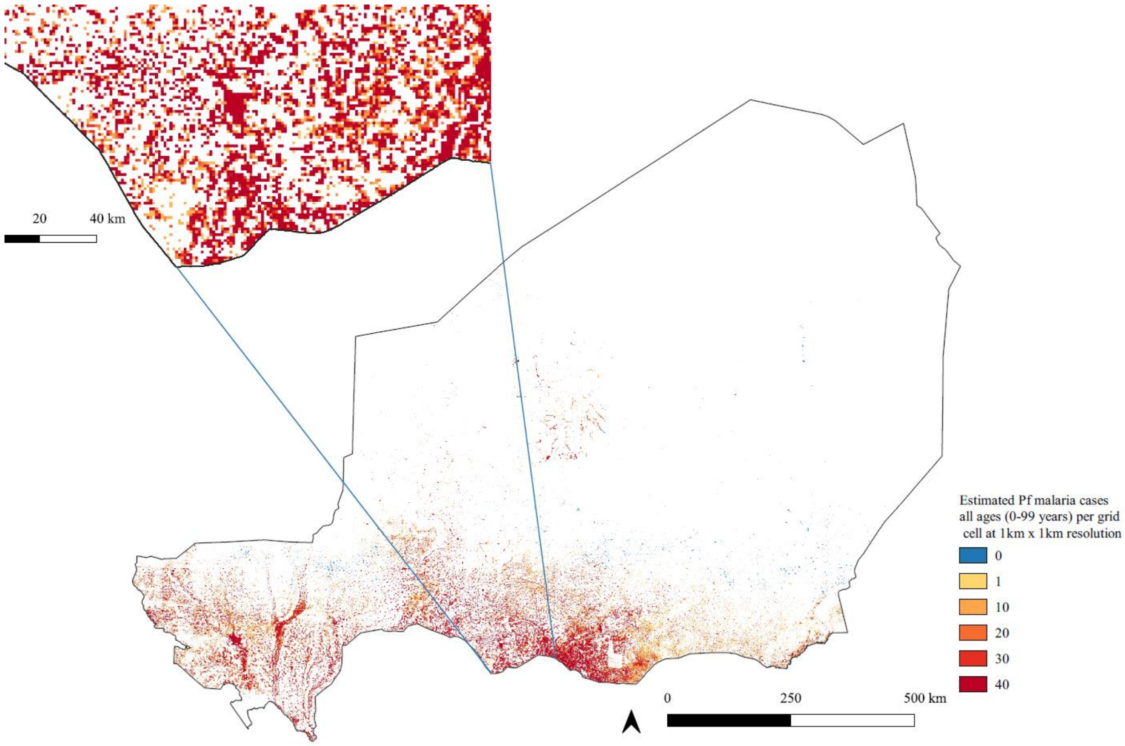

**Supplementary Figure 8. Digital elevation model at 100m x 100m resolution.**
NASA SRTMGL1 version 003 (approximately 30m x30m), resampled to 100m x 100m and 1km x 1km (later not shown). Accessed 4 October 2018. Inset near Madarounfa commune in the Maradi region.[1]




**Supplementary Figure 9. Estimated population count in 2013 (persons per grid cell) at 1km x 1km resolution.** Population layers produced at 100m x 100m resolution and 1km x 1km resolution. 1km x 1km shown here for ease of visualization. HRSL 2015 at approximately 30m x 30m resampled to 100m x 100m and 1km x 1km resolutions and adjusted to Worldpop population totals for 2013 at administrative level 3 (commune). Inset near Madarounfa commune in the Maradi region. Source: Derived from Facebook Connectivity Lab and Center for International Earth Science Information Network - CIESIN - Columbia University. 2016. High Resolution Settlement Layer (HRSL). Source imagery for HRSL © 2016 DigitalGlobe. Accessed 4 October 2018.[2] WorldPop (www.worldpop.org - School of Geography and Environmental Science, University of Southampton; Department of Geography and Geosciences, University of Louisville; Département de Géographie, Université de Namur) and Center for International Earth Science Information Network (CIESIN), Columbia University (2018). Global High Resolution Population Denominators Project - Funded by The Bill and Melinda Gates Foundation (OPP1134076). https://dx.doi.org/10.5258/SOTON/WP00645. Accessed 4 October 2018.[3]



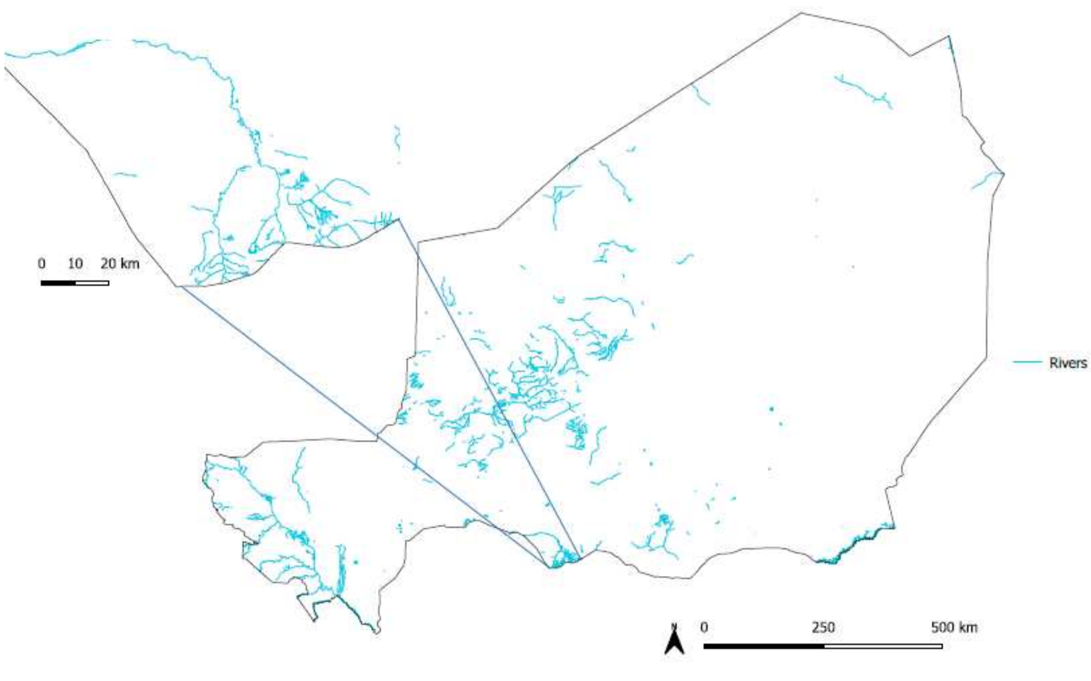

**Supplementary Figure 10. Mean U5 deaths in 2013 at 1km x 1km.**
Derived from the mean U5 mortality rate in 2013 (IHME) at 5km x 5km, resampled to 1kmx1km and multiplied by the 2013 under-five population layer (derived from HRSL and Worldpop population layers, described in Methods). U5=under-five. Source: Institute for Health Metrics and Evaluation (IHME). Low- and Middle-Income Country Neonatal, Infant, and Under-5 Mortality Geospatial Estimates 2000-2017. Seattle, United States: Institute for Health Metrics and Evaluation (IHME), 2019.[4] Described in Burstein R, Henry JH, Collison ML, Marczak LB, Sligar A, Watson S, et al. Mapping 123 million neonatal, infant, and child deaths between 2000 and 2017. Nature. 16 October 2019.[5]



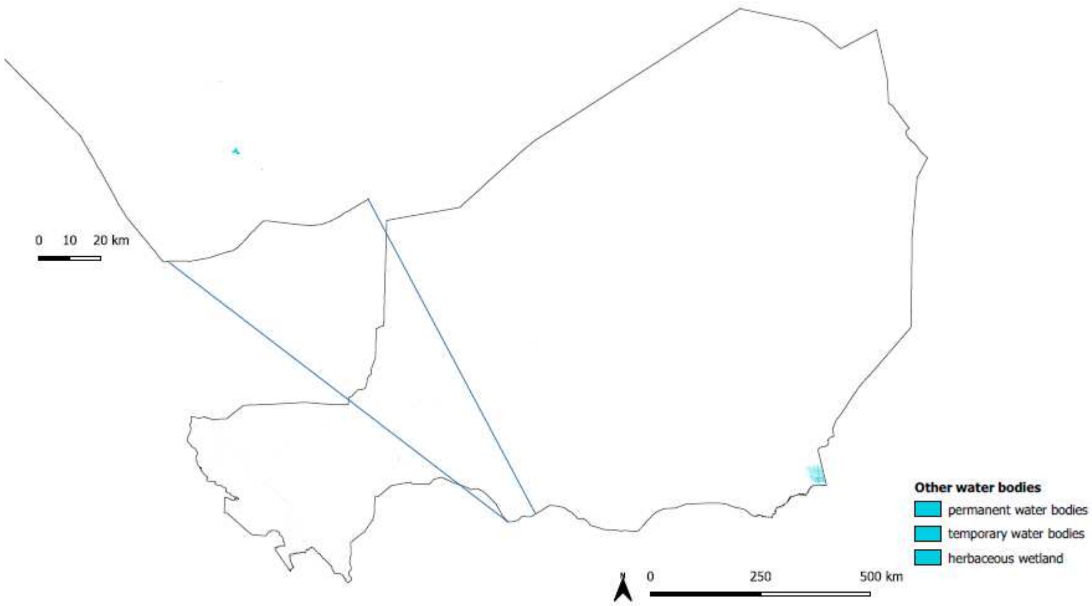

**Supplementary Figure 11. Estimated *Pf* malaria cases among all ages (0-99 years) per grid cell at 1km x 1km resolution.**

Annual mean incidence of Plasmodium falciparum (Pf) malaria among all ages (0-99 years) in 2013 globally at 2.5 arcminutes (approximately 5km x 5km) resolution from Weiss et al 2019, reprojected to 1km x 1km resolution and multiplied by the estimated population in 2013 (see Methods). Source: Weiss DJ, Lucas TCD, Nguyen M, et al. Mapping the global prevalence, incidence, and mortality of Plasmodium falciparum, 2000–17: a spatial and temporal modelling study. Lancet 2019; published online June 19. http://dx.doi.org/10.1016/S0140-6736(19)31097-9.[6]

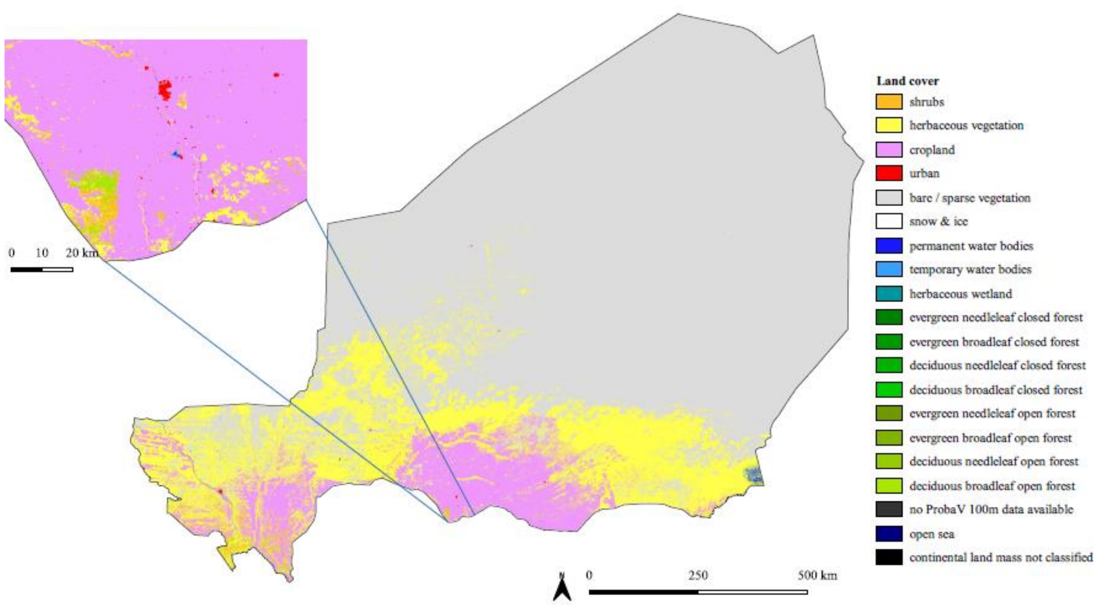

**Supplementary Figure 12. Road network**
Source: Humanitarian OpenStreetMap Team (HOT). Accessed 1 August 2018.[7]



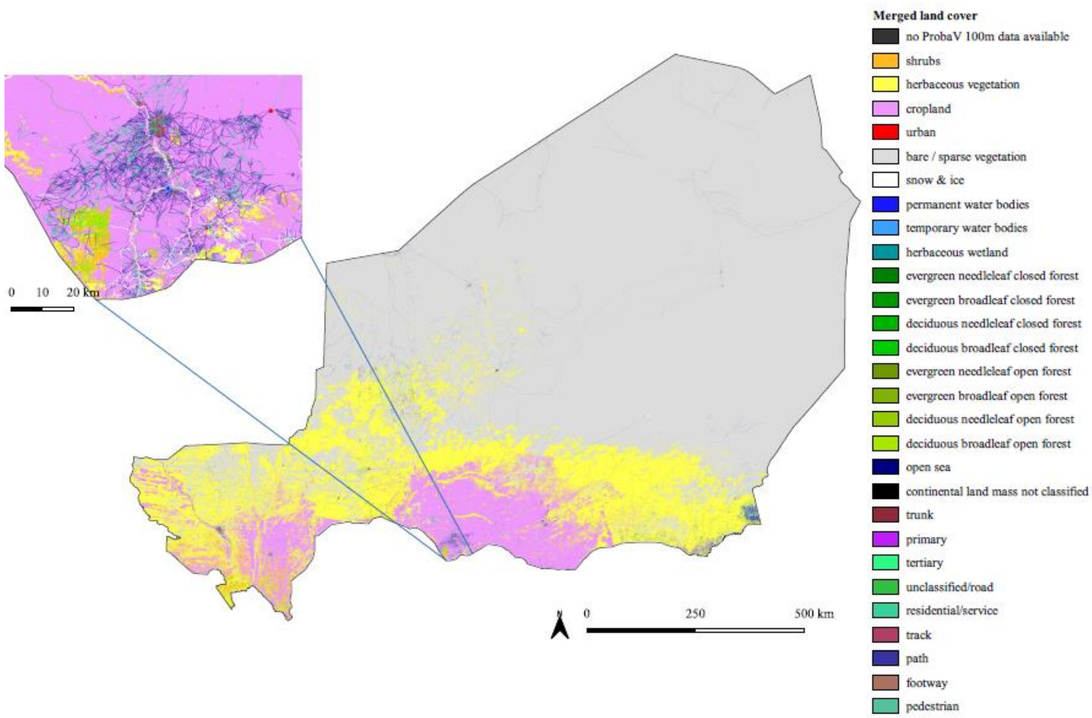

**Supplementary Figure 13. Rivers**
Source: Humanitarian OpenStreetMap Team (HOT). Accessed 15 January 2018. Note: other water bodies included in the land cover layer.[8]



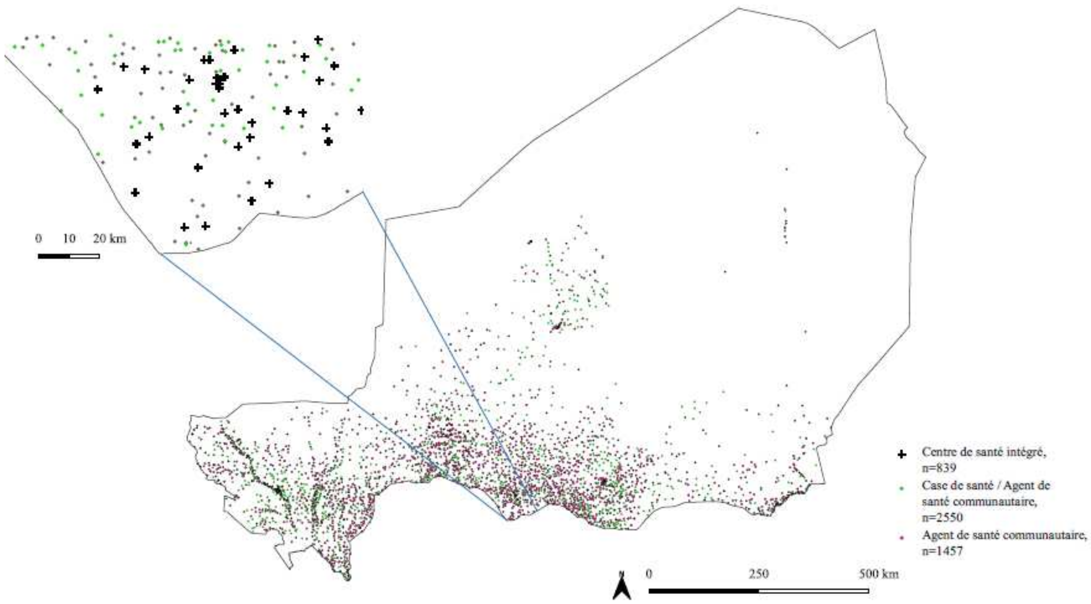

**Supplementary Figure 14. Other water bodies**
Includes the following land classes from the source below: permanent water bodies, temporary water bodies and herbaceous wetland. Source: Buchhorn, M., Smets, B., Bertels, L., Lesiv, M., Tsendbazar, N.-E., Masiliunas, D., Herold, M., Fritz, S. (2019). Copernicus Global Land Service: Land Cover 100m, Collection 2, epoch 2018 Africa Demo (Version V2.1.1). Zenodo. DOI:10.5281/zenodo.3518087. Copernicus Global Land Service, accessed on 27 March 2018 at https://land.copernicus.eu/global/products/lc.[9]



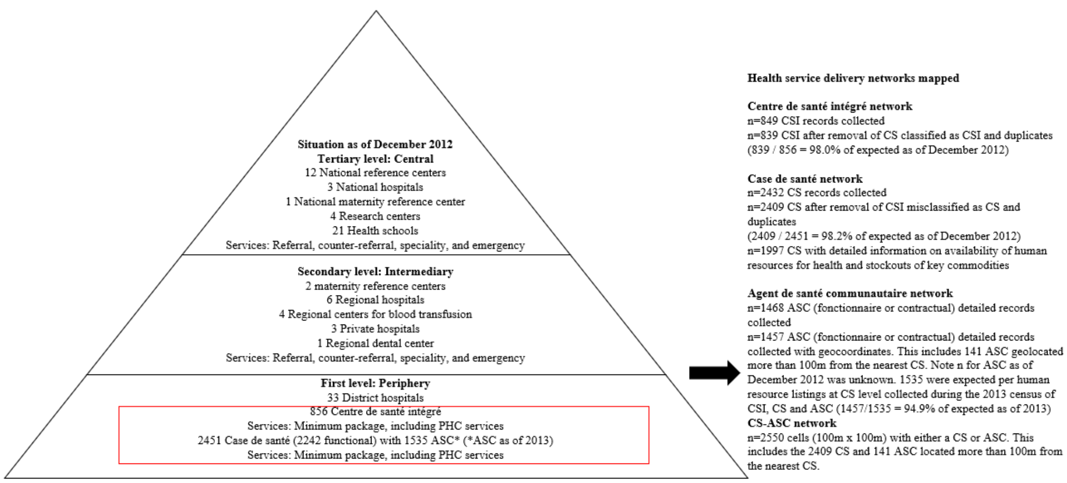
**Supplementary Figure 15. Land cover at 100m x 100m resolution.**
Land cover at 100m x 100m and 1km x 1km resolutions (latter not shown). Discreet land cover classes are based on the UN Land Cover Classification System (LCCS). Source: Buchhorn, M., Smets, B., Bertels, L., Lesiv, M., Tsendbazar, N.-E., Masiliunas, D., Herold, M., Fritz, S. (2019). Copernicus Global Land Service: Land Cover 100m, Collection 2, epoch 2018 Africa Demo (Version V2.1.1). Zenodo. DOI:10.5281/zenodo.3518087. Copernicus Global Land Service, accessed on 27 March 2018 at https://land.copernicus.eu/global/products/lc.[9]




**Supplementary Figure 16. Merged land cover at 100m x 100m resolution.**
Merged land cover at 100m x 100m and 1km x 1km resolutions (latter not shown) derived using the "Merge land cover" tool in AccessMod v5[10]. Road classes "construction" and "bridleway" not shown due to space limitations.




**Supplementary Figure 17. Health service delivery locations**
Source: UNICEF, Institut National de la Statistique, Ministère de la Santé Publique. 2013 Census of Agents de Santé Communautaire, Cases de Santé and Centres de Santé Intégrés.[11]




**Supplementary Figure 18. Health system pyramid and health service delivery networks mapped**

**Data**

**Administrative boundaries**

We obtained vector shapefiles for administrative boundaries 0-3 developed by the Institut Géographique National Niger (IGNN) and OCHA in 2017 with updates from the REACH Initiative in 2018, accessed 14 February 2018, at https://data.humdata.org/dataset/niger-administrative-boundaries.[12] We reprojected the shapefiles for the administrative boundaries 0-3 from the Coordinate Reference System (CRS) EPSG:4326, WGS 84 to the CRS EPSG:32632 - WGS 84 / UTM zone 32N using the GDAL "Warp" tool in QGIS 3.12.0-Bucareşti.[13]

**Health system pyramid and health service delivery networks**

The health system of Niger included a public and private sector organized in a decentralized, pyramidal structure with three administrative levels: a central level composed of the cabinet of the Minister of Public Health, the Secretary General and General/National Directorates, responsible for strategy and managing national hospitals, and national maternities and referral centers; a regional level composed of Regional Directorates, responsible for managing regional hospitals, and regional maternities and referral centers; and a district level, composed of District Health Teams, responsible for managing district hospitals, a network of first-level health facilities called *centre de santé intégré* (CSI), a network of community health posts called *case de santé* (CS) – attached to the network of CSI – as well as a small network of private clinics and practices.[14]

Structures at the central and regional levels, as well as district hospitals provided referral, counter referral, specialist, and emergency services not available at the peripheral level through the *centre de santé intégré* (CSI) and *Case de santé* (CS) networks.[15] As of December 2012, there were 856 CSI, offering a minimum package of services, focused on primary health care, referral from and counter-referral to the CS, and supervision of the CS. CSI were typically staffed by nurses and in certain large communes by a generalist doctor and midwives.[14] According to national norms, CSI in rural areas (CSI Type I) serve a maximum population of 10000 and a maximum population of 5000 in rural areas with low population density, while CSI in urban areas or areas with high population density (CSI Type II) serve a maximum population of 15000.[15] As of December 2012, there were 2451 CS.[14] According to national norms, CS were attached to the CSI in the hierarchy of the health system, were intended to be situated beyond 5km from a CSI, and served a population of 2500 to 5000.[15] CS provided a minimum package of activities, focused on primary health care: case management for common infectious diseases, including acute respiratory illness, diarrhea, and malaria, referral services for severe or complicated cases, reproductive health services (family planning, antenatal care, assisted delivery and referral for pregnancies at elevated risk or with complications) and health promotion.[15] CS typically were staffed by a cadre of full-time *agent de santé communautaire* (ASC), community health workers, who were typically contracted, paid a monthly salary of roughly $100 USD, had completed at least secondary education, and received a six-month pre-deployment basic training on the minimum package and a six-day training on iCCM after deployment.[11,15—17] ASC typically provided services from the CS (i.e. fixed site service delivery) and did not typically provide mobile services or household visits. In 2013, there were 1535 ASC (1154 male and 381 female).[11] In addition 21.6% of CS had at least one nurse in 2013 (232 nurses were deployed at CS in 2013) and 42.0% of CS had at least one *relais communautiare* (RC) – a network of volunteer community health workers attached to the CS and providing health promotion and prevention interventions in the communities within the catchment area of the CS (2672 RC were supporting CS in 2013).[11]

***Centre de santé intégré* network**

Through a data sharing agreement with UNICEF, we obtained a vector point shapefile dataset in the CRS EPSG:4326, WGS 84 with the global positioning system (GPS) coordinates and basic identification information for all CSI (n=849) in Niger collected through a national, georeferenced census of CSI, CS and ASC conducted in 2013 by the National Institute of Statistics of Niger (INS), Ministry of Public Health (MoPH) of Niger, and UNICEF.[11] We found that 10 records were misclassified as CSI and these were removed, leaving 839 CSI. We triangulated the CSI dataset with the CS dataset (below) to ensure no duplication or misclassification of CSI as CS and *vice versa*. We reprojected the CSI shapefile to the CRS EPSG:32632 – WGS 84 / UTM zone 32N, using the GDAL "Warp" tool in QGIS 3.12.0-Bucareşti.[13] For our analysis of geographic coverage, the maximum population capacity of a CSI was set at a population of 10000 for both CSI Type I CSI Type II to simplify the analysis and because we deemed a maximum population capacity of 15000 for CSI in urban areas (as noted above) unrealistic.

***Case de santé* network**

We obtained, through the data sharing agreement with UNICEF noted above, a vector point shapefile dataset in the CRS EPSG:4326, WGS 84 with the GPS coordinates and basic identification information for 2409 CS in Niger collected through a national, georeferenced census of CSI, CS and ASC conducted in 2013 by the INS of Niger, MoPH of Niger, and UNICEF.[11] Data was collected for 2432 structures (n=1703 structures with geocoordinates and complete interviews with the responsible health agent, n=294 structures with geocoordinates and partially complete interviews with the responsible health agent, n=3 structures with geocoordinates where the responsible agent declined to be interviewed, n=3 structures with geocoordinates but missing interviews with the responsible agent, and n=429 structures with geocoordinates that were closed at the time of the census or the responsible agent was absent. We excluded 23 CS records due to miscoding of CSI as CS, leaving 2409 CS records. In our analysis we included all CS records (n=2409) with geocoordinates, including those that were closed at the time of the census or the agent was absent – with the understanding that closures of CS and absences of responsible agents are typically temporary and vary from year to year[11,18]. We reprojected the CS shapefile to the CRS EPSG:32632 – WGS 84 / UTM zone 32N, using the GDAL "Warp" tool in QGIS 3.12.0-Bucareşti.[13] For analyses at 1km resolution (geographic coverage, targeting and scale-up analysis) we adjusted GPS coordinates, where necessary, for barriers at 1km resolution – these changes were maintained for analyses at 100m resolution (geographic accessibility). Detailed data on the availability of human resources for health and stockouts was available for a subset (n=1997) of the 2409 CS and our analysis of geographic accessibility to CS with available professional/trained human resources for health (e.g. had a nurse – registered nurse, certified nurse, state registered nurse, senior nursing technician – or ASC) and CS without severe stockouts of key commodities for case management of malaria, pneumonia and diarrhea was based on this subset of the CS data. A "severe stockout" was defined as a stockout lasting seven days or longer. We considered key commodities for the case management of malaria (rapid diagnostic test, Artemether/lumefantrine 20/120 mg) pneumonia (cotrimoxazole in pill or syrup form), diarrhea (low osmolarity oral rehydration salt sachets and zinc sulfate 20 mg) and acute malnutrition (ready-to-use therapeutic food (RUTF)). For our analysis of geographic coverage, the maximum population capacity of a CS was set at a population of 2500.

***Agent de santé communautaire* network**

In 2013, there were 1535 ASC (1154 male and 381 female).[11] We obtained, through the data sharing agreement with UNICEF noted above, a vector point shapefile dataset in the CRS EPSG:4326, WGS 84 with GPS coordinates of the work location of the ASC and detailed information for 1468 ASC (95.6% of the 1535 expected ASC) from 1421 CS, including socio-demographics, year of deployment, initial training and refresher training for specific interventions collected through a national, georeferenced census of CSI, CS and ASC conducted in 2013 by the INS of Niger, MoPH of Niger, and UNICEF.[11] We found 11 ASC without GPS coordinates and excluded them from analysis, leaving 1457 ASC (94.9% of the 1535 expected ASC). We reprojected the ASC shapefile to the CRS EPSG:32632 – WGS 84 / UTM zone 32N, using the GDAL "Warp" tool in QGIS 3.12.0-Bucareşti.[13] For analyses at 1km resolution (geographic coverage, targeting and scale-up analysis) we adjusted GPS coordinates, where necessary, for barriers at 1km resolution – these changes were maintained for analyses at 100m resolution (geographic accessibility).

We prepared separate vector point files using CRS EPSG:32632 – WGS 84 / UTM zone 32N for the ASC network, according to gender of the ASC, year of deployment and training on iCCM. We found that 1316 (90.4%) of ASC were located at the CS to which they were attached but 141 (9.6%) had unique GPS coordinates greater than 100m from the nearest CS. For our analysis of geographic coverage, the maximum population capacity of an ASC was set at a population of 2500. For ASC based at a CS, the maximum population capacity was maintained at 2500 (i.e. they were considered as contributors to the maximum population capacity of the CS).

**CS-ASC network**

We prepared a vector point shapefile with CRS EPSG:32632 – WGS 84 / UTM zone 32N that combined the CS (n=2409) and ASC with unique GPS coordinates (n=141) into a single CS-ASC network (n=2550). For our analysis of geographic coverage, the maximum population capacity of a CS-ASC was set at a population of 2500.

**Optimized CS-ASC network**

For our targeting analysis, we prepared three vector point shapefiles for hypothetical CS-ASC networks: 1) optimizing geographic coverage of the estimated residual population in 2013 beyond the geographic coverage of the

CSI network (60-minutes walking considering maximum population capacity) 2) optimizing geographic coverage of the estimated residual under-five deaths in 2013 beyond the geographic coverage of the CSI network and 3) optimizing geographic coverage of the estimated residual *Pf* malaria cases among all ages (0-99) in 2013 beyond the geographic coverage of the CSI network to compare against the existing CS-ASC network, given the same number of CS-ASC as the existing CS-ASC network (n=2550), at 1km x 1km resolution. The optimized CS-ASC networks were prepared using the following steps:

1. Using the population beyond the geographic coverage of the CSI network -- i.e. the population beyond the 60-minute catchment of the CSI network, with maximum population capacity of 10000 population per CSI, we used the "Raster calculator" in QGIS 3.12.0-Bucareşti[13] to create a dummy raster containing cells at 1km x 1km resolution with greater than or equal to 500 people. The cut-off of greater than or equal to 500 people was chosen as it reflects 25% of the maximum population capacity (2500 people) of a CS-ASC[16] and we assumed deployment of CS-ASC to cells with less than 500 people would be contrary to country norms[16].
2. We vectorized the raster from step 1 using the "Polygonize" tool in QGIS 3.12.0-Bucareşti,[13] resulting in a point vector shapefile of 5796 potential CS-ASC sites.

See the section below on the Targeting analysis for further details on preparation of these datasets.

**Scaled-up *relais communautaire* network**

The MoPH in Niger plans to scale-up the network of CHWs called *relais communautaire* (RC) for two contexts: 1) rural contexts at a ratio of 2 RC per 1000 population in communities beyond 5km of the CS-ASC or CSI networks to provide preventive, promotional and curative (e.g. iCCM) interventions and 2) in urban/peri-urban contexts at a ratio of 1 RC per 1000 population in communities within 5km of the CS-ASC and CSI networks to provide preventive and promotional interventions. For our scale-up analysis, we focus on the former. We prepared a hypothetical "optimized" RC network (n=3295) to cover the population in cells with at least 500 people in 2013 beyond the geographic coverage of the existing CSI and CS-ASC networks at 1km x 1km resolution using the following steps:

1. Using the population beyond the geographic coverage of the existing CS-ASC network – i.e. the population beyond the 60-minute catchment of the CS-ASC network, with maximum population capacity of 2500 population per CS-ASC we used the "Raster calculator" in QGIS 3.12.0-Bucareşti[13] to create a dummy TIFF raster containing cells at 1km x 1km resolution with greater than or equal to 500 people.
2. We vectorized the raster from step 1 using the "Polygonize" tool in QGIS 3.12.0-Bucareşti,[13] resulting in a point vector shapefile of 3521 candidate RC sites, with 7042 RC at a ratio of 2 RC per site or 2 RC per 1000 people based on the national norm.[16]
3. In our scale-up analysis (described below) we filtered out candidate sites with a realized capacity (i.e., the population covered within the catchment) of less than 500 population, leaving 3296 candidate sites for the scale-up analysis.

**DEM**

We obtained 174 tiles of a gridded digital elevation model (DEM) – the NASA Shuttle Radar Topography Mission Global 1 arc second (SRTMGL1) dataset version 3.0, with a resolution of approximately 30 meters (m) x 30m (0.000277778 decimal degrees) for the area including Niger.[1] The SRTMGL1 was retrieved 4 October 2017 from the online EarthExplorer, courtesy of the NASA EOSDIS Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota, https://earthexplorer.usgs.gov/. More information on the SRTMGL1 is available at https://lpdaac.usgs.gov/node/527. We used the "merge" function in QGIS 3.12-Bucareşti[13] to mosaic the original tiles into one georeferenced Tagged Information File Format (GeoTIFF) raster. For our analysis at 100m x 100m resolution (geographic accessibility analysis) we prepared a DEM raster at 100m x 100m resolution using the GDAL "warp" tool in QGIS 3.12.0-Bucareşti[13] to reproject the CRS of the original file from EPSG:4326, WGS 84 to the CRS EPSG:32632 - WGS 84 / UTM zone 32N, resample the resolution to 100m x 100m using bilinear as the resampling method and clip the file to the extent of the administrative level 3 (adm3) shapefile (see GeoTIFF file "r_NER_DEM_100m_final.tif" in Supplementary Appendix 3). For our analysis at 1km x 1km resolution (geographic coverage, targeting and scale-up analysis) we prepared a GeoTIFF DEM raster at 1km x 1km resolution using the GDAL "warp" tool in QGIS 3.12.0-Bucareşti[13] and the process described above (see the GeoTIFF file "r_NER_DEM_1km_final.tif" in Supplementary Appendix 1c at https://doi.org/10.6084/m9.figshare.13536779.v6).

**Land cover**

We obtained a GeoTIFF raster for land cover in Africa [c_gls_LC100-LCCS_201501010000_AFRI_PROBAV_1.0.1] at a resolution of approximately 100m x 100m from the Copernicus Global Land Service,[9] accessed on 27 March 2018 at https://land.copernicus.eu/global/products/lc. The land cover dataset contains discreet land cover classes based on the UN Land Cover Classification System (LCCS). Further details on the Copernicus land cover data set are available at https://land.copernicus.eu/global/products/lc. For our analysis at 100m x 100m resolution (geographic accessibility analysis) we prepared a GeoTIFF land cover raster (see the GeoTIFF file "r_NER_land_100m_final.tif" in Supplementary Appendix 3) using the GDAL "warp" tool in QGIS 3.12.0-Bucareşti[13] to reproject the CRS from EPSG:4326 - WGS84 to EPSG:32632 - WGS 84 / UTM zone 32N, resample the resolution to 100m x 100m using nearest neighbor as the sampling method and clip the file to the extent of the final DEM. For our analysis at 1km x1km resolution (geographic coverage, targeting and scale-up analysis) we prepared a GeoTIFF land cover raster at 1km x 1km resolution using the GDAL "warp" tool in QGIS 3.12.0-Bucareşti[13] and the process described above (see the GeoTIFF file "r_NER_land_1km_final.tif" in Supplementary Appendix 1c at https://doi.org/10.6084/m9.figshare.13536779.v6).

**Roads**

We obtained a vector line shapefile for the road network in Niger developed by the Humanitarian OpenStreetMap Team, accessed on 1 August 2018, at https://data.humdata.org/dataset/hotosm_niger_roads.[7] To prepare the final roads file, we changed the column "Highway" to "label"; reclassified the road types using the standard OpenStreetMap categories described at https://wiki.openstreetmap.org/wiki/Key:highway; simplified the road typology by excluding road types with very few segments or of little importance/relevance to the study; added a "class" variable in order to enable linking with the travel time scenarios; and reprojected the CRS from EPSG:4326 - WGS84 to EPSG:32632 - WGS 84 / UTM zone 32N in alignment with the final DEM (see files t_NER_reclass_roads_OSM.xls, v_NER_roads_100m_final.shp and v_NER_roads_1km_final.shp in Supplementary Appendix 1c at https://doi.org/10.6084/m9.figshare.13536779.v6). As described below in the section on the merged land cover raster, for our analysis at 100m x 100m resolution we uploaded the vector line shapefile for the road network into our Accessmod v5 project at 100m x 100m resolution and used the merge land cover tool in Accessmod v5 to rasterize the vector line shapefile for the road network as part of the merged land cover raster at 100m x 100m resolution. For our analysis at 1km x 1km resolution (geographic coverage, targeting and scale-up analysis) we repeated the above within our Accessmod v5[10] project at 1km x 1km resolution.

**Rivers and Other Waterbodies**

Rivers and other waterbodies were considered barriers to movement, where they were not crossed by a road. We obtained vector line shapefiles for rivers from HOT Open Street Map (HOTOSM), accessed on 15 January 2018, at https://data.humdata.org/dataset/hotosm_niger_waterways.[8] For our analysis at 100m x100m resolution (geographic accessibility), we reprojected the CRS from EPSG:4326 - WGS84 to CRS EPSG:32632 - WGS 84 / UTM zone 32N in alignment with the final DEM (see file "v_NER_rivers_final.shp" in Supplementary Appendix 1c at https://doi.org/10.6084/m9.figshare.13536779.v6). As described below in the section on the merged land cover raster, for our analysis at 100m x 100m resolution we uploaded the vector line file for rivers into our Accessmod v5[10] project at 100m x 100m resolution and used the merge land cover tool in Accessmod v5[10] to rasterize the vector line shapefile for rivers as part of the merged land cover raster at 100m x 100m resolution. For our analysis at 1km x 1km resolution (geographic coverage, targeting and scale-up analysis) we repeated the above within our Accessmod v5[10] project at 1km x 1km resolution. Data on other water bodies (permanent and temporary) were already included as part of the land cover raster described above.

**Merged land cover**

For our geographic accessibility analysis, we prepared a merged land cover raster at 100m x 100m resolution using the "Merge land cover" tool in AccessMod v5[10] (see file "r_NER_land_merged_100m_final.tif" in Supplementary Appendix 1c at https://doi.org/10.6084/m9.figshare.13536779.v6). The process is described in detail in Ray et al, 2008.[10] In brief, the "Merge land cover" tool stacks, orders, and merges the road network, barriers (rivers and other waterbodies, the later from the land cover), and land cover files into a single raster dataset. For our analysis at 1km x 1km resolution (geographic coverage, targeting and scale-up analysis) we prepared a merged land cover raster at 1km x 1km resolution using the process described above within our Accessmod v5[10] project at 1km x 1km resolution (see the file "r_NER_land_merged_100m_final.tif").

**Travel scenario tables**

We developed travel scenario tables for the following scenarios walking in dry conditions and walking to the nearest road and then using motorized transportation in dry conditions (see files "t_NER_walk_dry.xls" and "t_NER_walk_veh_dry.xls" in Supplementary Appendix 1c at https://doi.org/10.6084/m9.figshare.13536779.v6). We set traveling speeds by mode of transportation (walking or walking + motorized transportation) for each land cover class and road class. Travel speeds were adapted from previous studies.[18,19]

**Population**

**Data preparation of population raster layers for the year 2013**

We obtained a GeoTiff raster for the estimated population count for Niger in 2015 adjusted to UN population estimates at roughly 30m x 30m resolution, the High Resolution Settlement Layer (HRSL) from https://data.humdata.org/dataset/highresolutionpopulationdensitymaps-ner, courtesy of Facebook Connectivity Lab and Center for International Earth Science Information Network (CEISIN) at Columbia University, accessed 6 August 2020.[2] The 2015 HRSL was developed with computer vision techniques and supervised machine learning applied to high resolution commercial satellite imagery from the DigitalGlobe, courtesy of Maxar[20] to identify and classify human-built structures, combined with population estimates from the Gridded Population of the World v4[21]. Further details are provided elsewhere[22]. We also obtained a GeoTiff raster for the estimated population count for Niger in 2013, adjusted to UN population estimates, at roughly 100m x 100m resolution in Geographic Coordinate system WGS84 from Worldpop, accessed 3 March 2020.[3] A random forest-based dasymetric redistribution approach was used to develop the Worldpop dataset and is described in detail elsewhere.[23] We prepared a GeoTiff raster file for the estimated population count in 2013 at 100m x 100m resolution that adjusted the HRSL GeoTiff of the estimated population count in 2015 to the GeoTiff from Worldpop for the estimated population count in 2013 [ner_ppp_2013] at the lowest administrative level (adm3) but maintained the population settlement footprint of the 2015 HRSL. We kept the footprint of the 2015 HRSL because we deemed it more appropriate for our purposes (analysis of geographic accessibility to health services) than the footprint of the Worldpop raster based on visual inspection against satellite imagery for Niger and recent assessments of its accuracy[23]. The population footprint of the Worldpop raster is "unconstrained", that is, smoothed across space,[24] including cells where there are no settlements,[25] whereas the HRSL is confined to cells with settlements.[2] We note that since the time of our analysis, an additional dataset – the World Settlement Footprint 2015[26]– has been made publicly available and Worldpop has developed population count datasets constrained to population settlement footprints.[27] Recent analyses suggest that modelling of population counts constrained to settlement footprints is improved through the use of multiple settlement footprints.[28,29]

We adjusted the counts of the 2015 HRSL dataset to the Worlpop counts for 2013 to align with our analysis for the year 2013. The raster layer for the estimated population count in the year 2013 at 100m x 100m resolution was used in our analysis of geographic accessibility, geographic coverage and scale-up. We used the following steps to prepare the raster layer for the population count in 2013 at 100m x 100m resolution:

1. We reprojected the original HRSL GeoTiff raster file for the population count in 2015 at approximately 30 meter resolution [population_ner_2018-10-01] from the CRS EPSG:4326 - WGS84 to the CRS EPSG:32632 – WGS 84 / UTM zone 32N using the GDAL Warp tool in QGIS 3.12.0-Bucareşti[13] and aggregated the reprojected raster to 100 meter resolution using the r.resamp.stats GRASS 7.8.2 plugin in QGIS 3.12.0-Bucareşti,[13] with sum as the aggregation method and the final DEM at 100 meter resolution as the extent, resulting in the file [r_NER_FB15N_unadj_100m].
2. We used the "Zonal statistics" tool in QGIS 3.12.0-Bucareşti[13] to calculate the count of the population from the original World pop population layer in 2013 [ner_ppp_2013] to a vector file for administrative level 3 in CRS WGS84 and used a spatial join to copy the population counts to the vector file for administrative level 3 in CRS EPSG:32632 – WGS 84 / UTM zone 32N [v_NER_adm3_final].
3. We used the "Zonal statistics" tool in QGIS 3.12.0-Bucareşti[13] to calculate the count of the population from the raster of the 2015 population at 100 meters [r_NER_FB15N_unadj_100m] from step 1 to the vector file [v_NER_adm3_final].
4. We created a ratio called "WP13tFB15" in the adm3 vector file [v_NER_adm3_final] that divided the population count at administrative level 3 from the original World pop population layer in 2013 from step 2 [ner_ppp_2013] by the population count at administrative level 3 from the HRSL population layer in 2015 from step 1 [r_NER_FB15N_unadj_100m].
5. We rasterized this ratio at 100m resolution using the "Rasterize" tool in QGIS 3.12.0-Bucareşti[13] [r_NER_ratWP13OtFB15N_100m] with the ratio from step 4 as the burn and the extent of the DEM at 100m resolution as the extent. Using raster calculator in QGIS 3.12.0-Bucareşti[13], we multiplied the rasterized ratio [r_NER_ratWP13OtFB15N_100m] by the HRSL population in 2015 at 100m x 100m resolution [r_NER_FB15N_unadj_100m] to create a GeoTiff raster for the population in the year 2013 [r_NER_FB13_100m_unadj_barriers].
6. We uploaded the file [r_NER_FB13_100m_unadj_barriers] into Accessmod v5 and redistributed the population on cells with barriers to cells without barriers within the same administrative level 3 boundaries, resulting in the final raster file for the population in the year 2013 [raster_population_r_NER_FB13_100m_final].

We repeated the steps above at 1km x 1km resolution to produce the GeoTiff raster of the population in 2013 at 1km x 1km resolution [r_NER_FB13_1km_final] (see Supplementary Appendix 1c at https://doi.org/10.6084/m9.figshare.13536779.v6).

**Data preparation of population raster layers for the years 2000-2012**

We obtained GeoTiff rasters for the estimated population count for the years 2000-2012 in Niger, adjusted to UN population estimates, at roughly 100m x 100m resolution in Geographic Coordinate system WGS84 from Worldpop, accessed 3 March 2020.[3] We prepared a GeoTiff raster layer for the population count in the year 2000 at 100m x100m resolution that matched the population count from the original Worldpop GeoTiff raster layer in 2000 [ ner_ppp_2000] at the lowest administrative level (adm3) but maintained the population settlement footprint of the 2015 HRSL. This assumes the actual population settlement footprint in 2000 would be similar to the HRSL, a limitation we acknowledge in the section on limitations. We used the raster layer for the population in the year 2000 to generate zonal statistics by administrative level for the estimated number and percent of the population in 2000 within 30 minutes and 60 minutes of the nearest ASC in 2000. We used the following steps to prepare the raster layer for the population count in 2000 at 100m x 100m resolution:

1. We reprojected the original Worldpop GeoTiff raster layer for the population in 2000 at approximately 90m x 90m resolution [ner_ppp_2000] from the CRS EPSG:4326 - WGS84 to the CRS EPSG:32632 – WGS 84 / UTM zone 32N using the GDAL Warp tool in QGIS 3.12.0-Bucareşti[13] and aggregated the reprojected raster to 100m x 100m meter resolution using the r.resamp.stats GRASS 7.8.2 plugin in QGIS 3.12.0-Bucareşti,[13] with sum as the aggregation method and the final DEM at 100m x 100m resolution as the extent, resulting in the file [r_NER_FB00_100m_unadj_barriers].
2. We used the "Zonal statistics" tool in QGIS 3.12.0-Bucareşti[13] to calculate the count of the population from the original World pop population layer in 2000 [ner_ppp_2000] to a vector file for administrative level 3 in CRS WGS84 and used a spatial join to copy the population counts to the vector file for administrative level 3 in CRS EPSG:32632 – WGS 84 / UTM zone 32N [v_NER_adm3_final].

3. We created a ratio called "WP00tFB13" in the adm3 vector file [v_NER_adm3_final] that divided the count from the original Worldpop population layer for 2000 from step 2 [ner_ppp_2000] by the population count from the population layer for 2013 [raster_population_r_NER_FB13_100m_final], which as described above, maintains the population settlement footprint of the 2015 HRSL.
4. We rasterized this ratio at 100m resolution using the "Rasterize" tool in QGIS 3.12.0-Bucareşti[13] [r_NER_ratWP00OtFB13F_100m_unadj_barriers] with the ratio from step 3 as the burn and the extent of the DEM at 100m x 100m resolution as the extent. Using raster calculator in QGIS 3.12.0-Bucareşti,[13] we multiplied the rasterized ratio [r_NER_ratWP00OtFB13F_100m_unadj_barriers] by the 2013 population [raster_population_r_NER_FB13_100m_final] to create a raster for the population in the year 2000 [r_NER_FB00_100m_unadj_barriers]. This approach effectively maintained the spatial distribution of the population as in 2013 while adjusting the 2013 population count downward to match the population from Worldpop for the year 2000 at the lowest administrative level [v_NER_adm3_final].
5. We uploaded the file [r_NER_FB00_100m_unadj_barriers] into Accessmod v5 and redistributed the population on cells with barriers to cells without barriers within the same administrative level 3 boundaries, resulting in the final raster file for the population in the year 2000 [raster_population_r_NER_FB00_100m_final].

For the years 2001-2012, we repeated the steps taken above for the year 2000 using the appropriate input population layers from Worldpop to create the rasterized ratios for each year:

2001: input file from Worldpop [ner_ppp_2001]; rasterized ratio file
[r_NER_ratWP01OtFB13F_100m_unadj_barriers]
2002: input file from Worldpop [ner_ppp_2002]; rasterized ratio file
[r_NER_ratWP02OtFB13F_100m_unadj_barriers]
2003: input file from Worldpop [ner_ppp_2003]; rasterized ratio file
[r_NER_ratWP03OtFB13F_100m_unadj_barriers]
2004: input file from Worldpop [ner_ppp_2004]; rasterized ratio file
[r_NER_ratWP04OtFB13F_100m_unadj_barriers]
2005: input file from Worldpop [ner_ppp_2005]; rasterized ratio file
[r_NER_ratWP05OtFB13F_100m_unadj_barriers]
2006: input file from Worldpop [ner_ppp_2006]; rasterized ratio file
[r_NER_ratWP06OtFB13F_100m_unadj_barriers]
2007: input file from Worldpop [ner_ppp_2007]; rasterized ratio file
[r_NER_ratWP07OtFB13F_100m_unadj_barriers]
2008: input file from Worldpop [ner_ppp_2008]; rasterized ratio file
[r_NER_ratWP08OtFB13F_100m_unadj_barriers]
2009: input file from Worldpop [ner_ppp_2009]; rasterized ratio file
[r_NER_ratWP09OtFB13F_100m_unadj_barriers]
2010: input file from Worldpop [ner_ppp_2010]; rasterized ratio file
[r_NER_ratWP10OtFB13F_100m_unadj_barriers]
2011: input file from Worldpop [ner_ppp_2011]; rasterized ratio file
[r_NER_ratWP11OtFB13F_100m_unadj_barriers]
2012: input file from Worldpop [ner_ppp_2012]; rasterized ratio file
[r_NER_ratWP12OtFB13F_100m_unadj_barriers]

We repeated step 3 above (redistribution of the population on cells with barriers to cells without barriers in Accessmod v5) for the 2001-2012 datasets, resulting in the following final population layers for the years 2001-2012 at 100m x 100m resolution to be used in our analysis of the trends in geographic accessibility between 2000-2013 (see Supplementary Appendix 1c at https://doi.org/10.6084/m9.figshare.13536779.v6):

2001: [ raster_population_r_NER_FB01_100m_final]
2002: [raster_population_r_NER_FB02_100m_final]
2003: [raster_population_r_NER_FB03_100m_final]
2004: [raster_population_r_NER_FB04_100m_final]

2005: [raster_population_r_NER_FB05_100m_final]
2006: [raster_population_r_NER_FB06_100m_final]
2007: [raster_population_r_NER_FB07_100m_final]
2008: [raster_population_r_NER_FB08_100m_final]
2009: [raster_population_r_NER_FB09_100m_final]
2010: [raster_population_r_NER_FB10_100m_final]
2011: [raster_population_r_NER_FB11_100m_final]
2012: [raster_population_r_NER_FB12_100m_final]

**Data preparation of live birth raster layer for the year 2013**
We obtained a GeoTiff raster [NER_births_pp_v2_2015] for the estimated live birth count in 2015 for Niger, adjusted to UN population estimates, at roughly 1km x 1km resolution in Geographic Coordinate system WGS84 from Worldpop, accessed on February 18, 2021.[3] We prepared a GeoTiff raster layer for the estimated count of live births in 2013 at 1km x 1km resolution to be used in our targeting analysis for under-five deaths. We used the following steps:

1. Using the original raster for estimated live births in 2015 from Worldpop, we used Zonal Statistics in QGIS 3.12.0- Bucareşti[13] to obtain the estimated live births for 2015 at administrative level 3 in CRS EPSG:4326 - WGS84.
2. We used a spatial join in QGIS 3.12.0- Bucareşti[13] to join the variable for the estimated live births in 2015 from the administrative level 3 layer (CRS EPSG:4326 - WGS84) to the administrative level 3 layer in the project CRS EPSG:32632 – WGS 84 / UTM zone 32N.
3. We used Raster Calculator in QGIS 3.12.0- Bucareşti[13] to create a dummy raster at 1km x 1km resolution for the cells where the total population in 2013 was greater than 0, with the extent aligned to the extent of the raster for the estimated total population in 2013 at 1km x 1km resolution [raster_population_r_NER_FBpop2013_1km_final_dummy].
4. We reprojected the original raster for estimated live births from Worldpop to CRS EPSG:32632 – WGS 84 / UTM zone 32N using the GDAL Warp tool in QGIS 3.12.0-Bucareşti[13], with the extent of the estimated total population raster for 2013 at 1km x 1km [IHME_LMICS_U5M_2000_2017_Q_UNDER5_MEAN_Y2019M10D16_U5MR13_reproj_1km].
5. We used Raster Calculator in QGIS 3.12.0- Bucareşti[13] to multiply the reprojected raster for estimated live births in 2015 by the dummy raster for the estimated total population in 2013, resulting in a raster for estimated live births for 2015 constrained to the footprint of the raster of the estimated total population in 2013 in the project CRS EPSG:32632 – WGS 84 / UTM zone 32N at 1km x 1km resolution.
6. We ran a Zonal Statistics in QGIS 3.12.0- Bucareşti[13] for the reprojected raster for estimated live births in 2015 constrained to the footprint of the raster for the estimated total population in 2013 (from step 5 above) at administrative level 3 in CRS EPSG:32632 – WGS 84 / UTM zone 32N [r_NER_births_2015_unadjusted_to_2015_original].
7. Within the administrative level 3 in CRS EPSG:32632 – WGS 84 / UTM zone 32N we calculated a new variable called "RatB15OtN" for the ratio between the original estimate of live births in 2015 (step 2 above) to the new estimate of live births in 2015 from the reprojected layer constrained to the footprint of the raster for the estimated total population in 2013 (step 6 above).
8. We used the GDAL Rasterize (vector to raster) tool within QGIS 3.12.0-Bucareşti[13] to create a raster in CRS EPSG:32632 – WGS 84 / UTM zone 32N at 1km x 1km resolution, using the variable "RatB15OtN" in the administrative level 3 layer as the burn [r_NER_rat_Births15OtN_1km].
9. We used Raster Calculator in QGIS 3.12.0- Bucareşti[13] to multiply the raster of the ratio from step 8 above by the reprojected raster for the estimated live births in 2015 constrained to the footprint of the raster of the estimated total population in 2013 (step 5), effectively adjusting the estimated live births in 2015 from step 5 to match the totals from the original estimated live births in 2015 at administrative level 3 (step 2) and resulting in a raster of estimated live births for 2015 constrained to the raster of the estimated population in 2013 [r_NER_births15_final_1km].
10. We ran a Zonal Statistics in QGIS 3.12.0- Bucareşti[13] for the estimated live births in 2015 (from step 9) at administrative level 3 in CRS EPSG:32632 – WGS 84 / UTM zone 32N.

11. We used Raster Calculator to create a raster for the ratio of the raster for estimated live births in 2015 (from step 9) to the raster for estimated total population in 2015 from the HRSL [r_NER_FB15_1km_unadj_barriers] in CRS EPSG:32632 – WGS 84 / UTM zone 32N at 1km x 1km resolution.
12. We used Raster Calculator in QGIS 3.12.0- Bucareşti[13] to multiply the raster of the ratio of estimated live births in 2015 to the estimated total population in 2015 (from step 11) by the raster for the estimated total population in 2013, resulting in a raster for the estimated live births in 2013 [r_NER_births13_final_1km] (see Supplementary Appendix 1c at https://doi.org/10.6084/m9.figshare.13536779.v6).

**Estimated under-five deaths**

We used the following steps to prepare the raster layer for the estimated count of under-five (0-5 years old) deaths in Niger in 2013 at 1km x 1km resolution to be used in our targeting analysis:

1. We obtained a GeoTiff raster file [IHME_LMICS_U5M_2000_2017_Q_UNDER5_MEAN] for modelled pixel-level estimates of the mean probability of under-five (0-5 years old) mortality (also known as the under-five mortality rate or U5MR) in EPSG:4326 - WGS84 at 2.5 arcminutes (approximately 5km x 5km) resolution developed by the Institute for Health Metrics and Evaluation (IHME),[4,5] accessed on 3 March 2020, at http://ghdx.healthdata.org/lbd-data [IHME_LMICS_U5M_2000_2017_Q_UNDER5_MEAN].
2. We used Raster Calculator in QGIS 3.12.0- Bucareşti[13] to create a new raster equivalent to band 14 (U5MR for 2013) of the raster from step 1 in EPSG:4326 - WGS84 at approximately 5km x 5km resolution, maintaining the extent of the raster from step 1.
3. Using the GDAL Warp tool in QGIS 3.12.0- Bucareşti[13], we reprojected the raster for the U5MR in 2013 from step 1 above to CRS EPSG:32632 – WGS 84 / UTM zone 32N at 1km x 1km resolution, with nearest neighbor as the resampling method and the extent aligned to the raster for the total population in 2013 [IHME_LMICS_U5M_2000_2017_Q_UNDER5_MEAN_Y2019M10D16_U5MR13_reproj_1km].
4. We used Raster Calculator in QGIS 3.12.0- Bucareşti[13] to multiply the raster for the U5MR in 2013 from step 2 above by the raster for estimated live births in 2013, resulting in a raster for the number of U5 deaths in 2013 in CRS EPSG:32632 – WGS 84 / UTM at 1km x 1km resolution [r_NER_U5d13_final_1km].
5. We used Raster Calculator in QGIS 3.12.0- Bucareşti[13] to multiply the raster for the number of U5 deaths in 2013 by a dummy raster for the area beyond the geographic coverage (1hr catchment, considering capacity) of the existing CSI network at 1km x 1km resolution [r_NER_raster_popuation__residual_r_NER_gcCSI_60min_1km_prioritize_popAire_g0]], resulting in a raster for the number of U5 deaths beyond the geographic coverage of the CSI network in CRS EPSG:32632 – WGS 84 / UTM at 1km x 1km resolution [r_NER_rU5d13_final_1km]. See supplementary Appendix 1c at https://doi.org/10.6084/m9.figshare.13536779.v6).

Note that we did not need to adjust for the estimated under-five deaths on barriers because this step was conducted when preparing the raster for the estimated population under-five in 2013.

We repeated the steps above using GeoTiff raster files for the 95% lower bound estimate for U5 mortality rate [IHME_LMICS_U5M_2000_2017_Q_UNDER5_LOWER] and the 95% upper bound estimate for U5 mortality rate [IHME_LMICS_U5M_2000_2017_Q_UNDER5_UPPER] to create GeoTiff rasters for estimated lower bound number of U5 deaths and estimated upper bound U5 deaths in 2013.

**Estimated *Plasmodium falciparum* malaria cases**

We used the following steps to prepare a GeoTiff raster layer for the estimated count of *Plasmodium falciparum* malaria cases among all ages (0-99 years) in Niger in 2013 at 1km x 1km resolution to be used in our targeting analysis:

1. We obtained a GeoTiff raster file for modelled pixel-level estimates of the annual mean incidence of *Plasmodium falciparum* (*Pf*) malaria among all ages (0-99 years) in 2013 globally at 2.5 arcminutes (approximately 5km x 5km) resolution developed by the Malaria Atlas Project,[6] accessed on 29 July 2020, at https://malariaatlas.org/malaria-burden-data-download/ [2019_Global_Pf_Incidence_2013].

2. Using the GDAL Warp tool in in QGIS 3.12.0- Bucareşti[13], we reprojected the raster for mean incidence of *Pf* malaria (all ages) in 2013 to CRS EPSG:32632 – WGS 84 / UTM at 1km x 1km resolution, using the extent of the raster for the estimated total population in 2013 as the extent [2019_Global_Pf_Incidence_2013_reproj_1km].
3. We used the "Raster calculator" tool in QGIS 3.12.0 to prepare a GeoTiff raster for the count of *Pf* malaria among all ages (0-99 years) in 2013 at 1km x 1km resolution [r_NER_Cases13_1km] by multiplying the reprojected raster for the mean incidence of *Pf* malaria (all ages) in 2013 from step 2 [2019_Global_Pf_Incidence_2013_reproj_1km] by the raster for the estimated total population in Niger in 2013 [raster_population_r_NER_FBpop2013_1km_final ] with the CRS EPSG:32632 – WGS 84 / UTM zone 32N at 1km x 1km resolution, using the extent of the raster of the estimated population in 2013 as the extent.
4. We used the "Raster calculator" tool in QGIS 3.12.0-Bucareşti[13] to prepare a GeoTiff raster for the estimated count of residual *Pf* malaria cases in 2013 beyond the geographic coverage (1hr catchment, considering capacity) of the existing CSI network at 1km x 1km resolution [r_NER_rCases_1km] by multiplying the estimated count of *Pf* malaria cases in 2013 from step 3 above [r_NER_Cases13_1km ] by a dummy raster for the area with non-zero residual population beyond the geographic coverage of the existing CSI network in 2013 [r_NER_raster_popuation__residual_r_NER_gcCSI_60min_1km_prioritize_popAire_g0] (see Supplementary Appendix 1c at https://doi.org/10.6084/m9.figshare.13536779.v6).

Note that we did not need to adjust for the estimated *Pf* malaria cases on barriers because this step was conducted when preparing the raster for the estimated population in 2013.

We repeated the steps above using GeoTiff raster files for the 95% lower bound estimate for mean incidence of *Pf* malaria (all ages) in 2013 [pf_incidence_rate_LCI_Global_admin0_2013] and the 95% upper bound estimate for mean incidence of *Pf* malaria (all ages) in 2013 [pf_incidence_rate_UCI_Global_admin0_2013] to create GeoTiff rasters for estimated lower bound number of *Pf* malaria cases (all ages) and estimated upper bound *Pf* malaria cases (all ages) in 2013.

**Analysis**

**Geographic accessibility**

Research questions

1. What was geographic accessibility to the CSI network in 2013?
    a. What percentage of the population was within 30 min and 60 min of a CSI in 2013, assuming a walking scenario in dry conditions? How did this vary across geographies?
    b. What percentage of the population was within 30 min and 60 min of a CSI in 2013, assuming a scenario of walking to the nearest road and then using motorized transportation in dry conditions? How did this vary across geographies?
2. What was geographic accessibility to the CS network in 2013?
    a. What percentage of the population was within 30 min and 60 min of a CS in 2013, assuming a walking scenario in dry conditions? How did this vary across geographies?
    b. What percentage of the population was within 30 min and 60 min of a CS in 2013, assuming a scenario of walking to the nearest road and then using motorized transportation in dry conditions? How did this vary across geographies?
3. What was geographic accessibility to the ASC network?
    a. What percentage of the population was within 30 min and 60 min of an ASC in 2013, assuming a walking scenario in dry conditions? How did this vary across geographies?
    b. What percentage of the population was within 30 min and 60 min of an ASC in 2013, assuming a scenario of walking to the nearest road and then using motorized transportation in dry conditions? How did this vary across geographies?
    c. What was the contribution of ASC to additional geographic accessibility beyond the network of CSI and CS (without ASC) in 2013? Assuming a walking scenario in dry conditions? Assuming a scenario

of walking to the nearest road and then using motorized transportation in dry conditions? How did this vary across geographies?
d. How did geographic accessibility to an ASC evolve over time between 2000-2013? Assuming a walking scenario in dry conditions? Assuming a scenario of walking to the nearest road and then taking motorized transportation in dry conditions?
e. How did geographic accessibility to an ASC in 2013 differ by gender of the ASC?
f. What percentage of the population in 2013 was within 30 min and 60 min of an ASC trained on iCCM? Assuming a walking scenario in dry conditions? Assuming a scenario of walking to the nearest road and then using motorized transportation in dry conditions? How did this vary across geographies?

4. What was geographic accessibility to the CS-ASC network in 2013?
    a. What percentage of the population was within 30 min and 60 min of a CS-ASC in 2013, assuming a walking scenario in dry conditions? How did this vary across geographies? How did this vary by availability of trained human resources (nurse, ASC) and essential commodities?
    b. What percentage of the population was within 30 min and 60 min of a CS-ASC in 2013, assuming a scenario of walking to the nearest road and then using motorized transportation in dry conditions? How did this vary across geographies? How did this vary by availability of trained human resources (nurse, ASC) and essential commodities?

**Methods for Geographic Accessibility question 1**

We define accessibility coverage as the estimated percentage of people within a given travel time to the nearest health service delivery location of a given health service delivery network, accounting for travel speeds of different modes of transportation over different land cover classes and slope, with the direction of travel toward the health service delivery location.[10] We estimated accessibility coverage at 100m x 100m resolution for the CSI, CS and ASC networks in 2013 – and for the ASC network by gender, year of deployment (2000-2013), training, and availability of essential commodities – using 30-minute and 60-minute cutoffs for administrative levels 0-3 and the two travel scenarios. We used 30-minute and 60-minute cutoffs as previous analyses have shown careseeking decays as a function of travel time after these cutoffs[30] and they are clinically relevant (e.g. for prompt treatment of severe illness).[31] The analysis was constrained to national borders but allowed for travel across subnational administrative boundaries. We used the "geographic accessibility" module within AccessMod 5 (v5.6.48)[10] to calculate travel time layers and the "zonal statistics" module to calculate the zonal statistics for each travel time layer by administrative level.

Analysis

1. We conducted a geographic accessibility analysis of the existing CSI network in 2013 based on a travel scenario of walking in dry conditions scenario at 100m x 100m resolution using Accessmod v5.
    a. We used the following data inputs:
        i. Population: raster_population_r_NER_FB13_100m_final
        ii. Land cover merged: raster_land_cover_merged_r_NER_land_merged
        iii. Scenario table: table_scenario_walk_dry
        iv. Select existing health facilities layer (vector): v_NER_CSI
        v. ID field: id
        vi. Facility name field: nom_centre
        vii. Select zones layer (vector): adm3
            1. Select zones unique ID (integer): objectid
            2. Select zone name (text): nom_com
    b. We used the following analysis settings:
        i. Type of analysis: anisotropic
        ii. Direction of travel: towards facilities
        iii. Maximum travel time (minutes): 60
        iv. Options
            1. Compute population catchment area layer: Yes

2. Remove the covered population at each iteration: Yes
3. Compute a layer of population cells on barriers: Yes
4. Generate zonal statistics: Yes (adm 3)
5. Optimize dynamically computation according to the scenario: Yes
6. Add short tag: raster_travel_time_r_NER_ga_CSI_wd_100m

2. We repeated steps 1 using a travel scenario for walking to the nearest road, then using motorized transportation in dry conditions. [raster_travel_time_r_NER_ga_CSI_walkvehd_100m] (see Supplementary Appendix 1b at https://doi.org/10.5281/zenodo.4482969).
3. We used the "Zonal statistics" tool within Accessmod v5 to calculate the percent of the population within 30 minutes and 60 minutes travel time in 2013 for the walking in dry conditions scenario and the walking + motorized transportation in dry conditions scenario (see Table 1 and Supplementary Appendix 2).

**Methods for Geographic Accessibility research question 2**

We repeated the analysis described in Methods for Geographic Accessibility question 1, replacing the existing health facilities layer with the layer [v_NER_CS_100m_final]. This resulted in the raster travel time layers [raster_travel_time_r_NER_ga_CS_wd_100m] and [raster_travel_time_r_NER_ga_CS_walkvehd_100m] (see Supplementary Appendix 1b at https://doi.org/10.5281/zenodo.4482969). See Table 1 for zonal statistics from these travel time rasters and detailed results for administrative layers 0-3 in Supplementary Appendix 2.

**Methods for Geographic Accessibility question 3**

We repeated the analysis described in Methods for Geographic Accessibility question 1, as follows:

2000: Input [v_NER_ASC_detailed_ASC_le2000]; output travel time rasters [raster_travel_time_r_NER_ga_ASC_detailed_le2000_wd_100m] and [raster_travel_time_r_NER_ga_ASC_detailed_le2000_walkvehd_100m]

2001: Input [v_NER_ASC_detailed_ASC_le2001]; output travel time rasters [raster_travel_time_r_NER_ga_ASC_detailed_le2001_wd_100m] and [raster_travel_time_r_NER_ga_ASC_detailed_le2001_walkvehd_100m]

2002: Input [v_NER_ASC_detailed_ASC_le2002]; output travel time rasters [raster_travel_time_r_NER_ga_ASC_detailed_le2002_wd_100m] and [raster_travel_time_r_NER_ga_ASC_detailed_le2002_walkvehd_100m]

2003: Input [v_NER_ASC_detailed_ASC_le2003]; output travel time rasters [raster_travel_time_r_NER_ga_ASC_detailed_le2003_wd_100m] and [raster_travel_time_r_NER_ga_ASC_detailed_le2003_walkvehd_100m]

2004: Input [v_NER_ASC_detailed_ASC_le2004]; output travel time rasters [raster_travel_time_r_NER_ga_ASC_detailed_le2004_wd_100m] and [raster_travel_time_r_NER_ga_ASC_detailed_le2004_walkvehd_100m]

2005: Input [v_NER_ASC_detailed_ASC_le2005]; output travel time rasters [raster_travel_time_r_NER_ga_ASC_detailed_le2005_wd_100m] and [raster_travel_time_r_NER_ga_ASC_detailed_le2005_walkvehd_100m]

2006: Input [v_NER_ASC_detailed_ASC_le2006]; output travel time rasters [raster_travel_time_r_NER_ga_ASC_detailed_le2006_wd_100m] and [raster_travel_time_r_NER_ga_ASC_detailed_le2006_walkvehd_100m]

2007: Input [v_NER_ASC_detailed_ASC_le2007]; output travel time rasters

[raster_travel_time_r_NER_ga_ASC_detailed_le2007_wd_100m] and
[raster_travel_time_r_NER_ga_ASC_detailed_le2007_walkvehd_100m]

2008: Input [v_NER_ASC_detailed_ASC_le2008]; output travel time rasters
[raster_travel_time_r_NER_ga_ASC_detailed_le2008_wd_100m] and
[raster_travel_time_r_NER_ga_ASC_detailed_le2008_walkvehd_100m]

2009: Input [v_NER_ASC_detailed_ASC_le2009]; output travel time rasters
[raster_travel_time_r_NER_ga_ASC_detailed_le2009_wd_100m] and
[raster_travel_time_r_NER_ga_ASC_detailed_le2009_walkvehd_100m]

2010: Input [v_NER_ASC_detailed_ASC_le2010]; output travel time rasters
[raster_travel_time_r_NER_ga_ASC_detailed_le2010_wd_100m] and
[raster_travel_time_r_NER_ga_ASC_detailed_le2010_walkvehd_100m]

2011: Input [v_NER_ASC_detailed_ASC_le2011]; output travel time rasters
[raster_travel_time_r_NER_ga_ASC_detailed_le2011_wd_100m] and
[raster_travel_time_r_NER_ga_ASC_detailed_le2011_walkvehd_100m]

2012: Input [v_NER_ASC_detailed_ASC_le2012]; output travel time rasters
[raster_travel_time_r_NER_ga_ASC_detailed_le2012_wd_100m] and
[raster_travel_time_r_NER_ga_ASC_detailed_le2012_walkvehd_100m]

2013: Input [v_NER_ASC_detailed_ASC_le2013]; output travel time rasters
[raster_travel_time_r_NER_ga_ASC_detailed_le2013_wd_100m] and
[raster_travel_time_r_NER_ga_ASC_detailed_le2013_walkvehd_100m]

Female: Input [v_NER_ASC_detailed_ASC_female_100m]; output travel time rasters
[raster_travel_time_r_NER_ga_ASC_detailed_female_wd_100m] and
[raster_travel_time_r_NER_ga_ASC_detailed_female_walkvehd_100m]

Male: Input [v_NER_ASC_detailed_ASC_male_100m]; output travel time rasters
[raster_travel_time_r_NER_ga_ASC_detailed_male_wd_100m] and
[raster_travel_time_r_NER_ga_ASC_detailed_male_walkvehd_100m]

iCCM: Input [v_NER_ASC_detailed_iCCM_le2013_100m]; output travel time rasters
[raster_travel_time_r_NER_ga_ASC_detailed_iCCM_le2013_wd_100m] and
[raster_travel_time_r_NER_ga_ASC_detailed_iCCM_le2013_walkvehd_100m]

See Supplementary Appendix 1b at https://doi.org/10.5281/zenodo.4482969). See Table 1 for zonal statistics from these travel time rasters and detailed results for administrative layers 0-3 in Supplementary Appendix 2.

We calculated the additional contribution of the ASC network to geographic accessibility beyond the existing network of CSI and CS (without ASC) in 2013 at 60 minutes walking in dry conditions using the following steps:

1. We used the "Raster calculator" tool in QGIS 3.12.0-Bucarești[13] to prepare a raster [r_NER_ga_dummy_CS_without_ASC_wd_100m ] for the cells within 60 minutes walking in dry conditions of a CS in 2013, using the travel time raster [raster_travel_time_r_NER_ga_CS_wd_100m], but beyond 60 minutes walking in dry conditions of an ASC in 2013, using the travel time raster [raster_travel_time_r_NER_ga_ASC_detailed_le2013_wd_100m] at 100m resolution in CRS EPSG:32632 – WGS 84 / UTM zone 32N with the final DEM at 100m as the extent.
2. We used the "Raster calculator" tool in QGIS 3.12.0-Bucarești[13] to prepare a raster [r_NER_ga_dummy_additional_contribition_ASC_le2013_wd_100m] for the cells beyond 60 minutes of a CS

(without an ASC), using travel time raster [r_NER_ga_dummy_CS_without_ASC_wd_100m], and beyond 60 minutes of a CSI, using travel time raster [raster_travel_time_r_NER_ga_CSI_wd_100m] but within 60 minutes of an ASC, using travel time raster [raster_travel_time_r_NER_ga_ASC_detailed_le2013_wd_100m] walking in dry conditions 2013 at 100m resolution in CRS EPSG:32632 – WGS 84 / UTM zone 32N with the final DEM at 100m as the extent.

3. We used the "Raster calculator" tool in QGIS 3.12.0-Bucareşti[13] to multiply the dummy raster for the additional contribution of ASC in 2013 to geographic accessibility to basic health services beyond the existing CS (without ASC) and CSI networks [r_NER_ga_dummy_additional_contribition_ASC_le2013_wd_100m] by the travel time raster for geographic accessibility to an ASC in 2013 [raster_travel_time_r_NER_ga_ASC_detailed_le2013_wd_100m]. This resulted in a travel time raster for the areas with additional geographic accessibility beyond 60 minutes walking in dry conditions of a CSI or CS (without an ASC) due to the contribution of ASC in 2013 at 100m resolution in CRS EPSG:32632 – WGS 84 / UTM zone 32N with the final DEM at 100m as the extent [r_NER_ga_additional_contribition_ASC_le2013_wd_100m] (see Supplementary Appendix 1b at https://doi.org/10.5281/zenodo.4482969). See Table 1 for zonal statistics from these travel time rasters and detailed results for administrative layers 0-3 in Supplementary Appendix 2.

We repeated steps 1-4 above for the travel scenario walking to the nearest road and then taking motorized transportation, resulting in the a travel time raster for the areas with additional geographic accessibility beyond 60 minutes walking + motorized transportation in dry conditions of a CSI or CS (without an ASC) due to the contribution of ASC in 2013 at 100m resolution in CRS EPSG:32632 – WGS 84 / UTM zone 32N with the final DEM at 100m as the extent [r_NER_ga_additional_contribition_ASC_le2013_walkvehd_100m] (see Supplementary Appendix 1b at https://doi.org/10.5281/zenodo.4482969). See Table 1 for zonal statistics from these travel time rasters and detailed results for administrative layers 0-3 in Supplementary Appendix 2.

We repeated steps 1-4 above for ASC trained on iCCM, resulting in the a travel time raster for the areas with additional geographic accessibility to iCCM services beyond 60 minutes walking in dry conditions of a CSI or CS (without an ASC) due to the contribution of ASC trained on iCCM in 2013 at 100m resolution in CRS EPSG:32632 – WGS 84 / UTM zone 32N with the final DEM at 100m as the extent [r_NER_ga_additional_contribition_ASC_le2013_iCCM_wd_100m] (see Supplementary Appendix 1b at https://doi.org/10.5281/zenodo.4482969). See Table 1 for zonal statistics from these travel time rasters and detailed results for administrative layers 0-3 in Supplementary Appendix 2.

Finally we repeated steps 1-4 above for ASC trained on iCCM, using the walking + motorized transportation travel scenario, resulting in the a travel time raster for the areas with additional geographic accessibility to iCCM services beyond 60 minutes walking + motorized transportation in dry conditions of a CSI or CS (without an ASC) due to the contribution of ASC trained on iCCM in 2013 at 100m resolution in CRS EPSG:32632 – WGS 84 / UTM zone 32N with the final DEM at 100m as the extent [r_NER_ga_additional_contribition_ASC_le2013_iCCM_walkvehd_100m] (see Supplementary Appendix 1b at https://doi.org/10.5281/zenodo.4482969). See Table 1 for zonal statistics from these travel time rasters and detailed results for administrative layers 0-3 in Supplementary Appendix 2.

We used the "Zonal statistics" tool in Accessmod v5 to calculate the percent of the population beyond 60 min of a CSI and CS (without an ASC) that were within 30 minutes and 60 minutes of an ASC in 2013, using walking and walking + motorized transportation travel scenarios. See Table 1 for zonal statistics from these travel time rasters and detailed results for administrative layers 0-3 in Supplementary Appendix 2.

**Methods for Geographic Accessibility question 4**

We repeated steps 1-3 from research question 1, using the following facility inputs:

1. CS-ASC network
2. CS-ASC network without a severe stockout of any iCCM commodity (severe stockout=stockout of any iCCM commodity lasting longer than seven days; iCCM commodities = RDT and AL for malaria, low osmolarity

ORS and zinc sulfate for diarrhea, cotrimoxazole (pill or syrup) for pneumonia. A stockout of any of these commodities lasting longer than 7 days resulted in the CS being considered as a CS with a severe stockout of any iCCM commodity.)
3. CS-ASC network with trained human resources (nurse and/or ASC)
4. CS-ASC network with trained human resources (nurse and/or ASC) and no stockout of any iCCM commodity (severe stockout=stockout of any iCCM commodity lasting longer than seven days; iCCM commodities = RDT and AL for malaria, low osmolarity ORS and zinc sulfate for diarrhea, cotrimoxazole (pill or syrup) for pneumonia. A stockout of any of these commodities lasting longer than 7 days resulted in the CS being considered as a CS with a severe stockout of any iCCM commodity.)
5. CS-ASC network with trained human resources (nurse and/or ASC) and no severe stockout of RDT or AL (severe stockout=stockout of any iCCM commodity lasting longer than seven days; iCCM commodities = RDT and AL for malaria)
6. CS-ASC network with trained human resources (nurse and/or ASC) and no severe stockout of ORS or zinc (severe stockout=stockout of any iCCM commodity lasting longer than seven days; ORS = low osmolarity oral rehydration solution)
7. CS-ASC network with trained human resources (nurse and/or ASC) and no severe stockout of cotrimoxazole (pill or syrup) (severe stockout=stockout of any iCCM commodity lasting longer than seven days; cotrimoxazole was the first-line antibiotic for pneumonia)
8. CS-ASC network with trained human resources (nurse and/or ASC) and no severe stockout of RUTF (severe stockout=stockout of any iCCM commodity lasting longer than seven days; RUTF=ready-to-eat therapeutic food)

See Supplementary Appendix 1b at https://doi.org/10.5281/zenodo.4482969). See Table 1 for zonal statistics from these travel time rasters and detailed results for administrative layers 0-3 in Supplementary Appendix 2.

**Geographic coverage**

We defined geographic coverage as the theoretical catchment area of a health service delivery location, within a maximum travel time, accounting for the mode of transportation and the maximum population capacity of the type of health service delivery location.[10] We used the "geographic coverage" module of AccessMod 5 (v5.6.48)[10] to estimate geographic coverage for the CSI and CS-ASC networks in 2013 at 1km x 1km resolution for the two travel scenarios. The maximum travel time was set at 60 minutes. The maximum population capacity was set at 10000 for CSI and 2500 for CS-ASC based on the norms of the MOPH of Niger.[15] The maximum extent of a catchment was therefore delimited by the maximum travel time of 60 minutes except in cases where the estimated population in the catchment exceeded the maximum population capacity of the health service delivery location – in which case the extent of the catchment was smaller than the maximum travel time and was defined by the area containing the estimated population, up to the maximum population capacity.

Research questions

1. What percentage of the estimated population was covered by the CSI network in 2013?
2. What percentage of the estimated residual population beyond the geographic coverage of the existing CSI network was covered by the CS-ASC network in 2013?
3. What percentage of the estimated population was covered by the combination of the CSI and CS-ASC networks in 2013?

**Methods for Geographic Coverage research question 1**

We conducted a geographic coverage analysis of the estimated population covered by the existing CSI network in 2013, with each CSI catchment defined by a maximum travel time of 60 min (walking or walking + motorized vehicle) and maximum population capacity of 10000.

Analysis

1. Geographic coverage analysis of the existing CSI network in 2013: We completed a geographic coverage analysis for the CSI network in 2013 considering maximum population capacity (10000 people) using the variable "capacity" and processing order based the variable estimated residual population within a 60-minute catchment (walking) of each CSI. This provided the final outputs for the CSI geographic coverage analysis. This provided the final outputs for the CSI geographic coverage analysis.
    a. We used the following data inputs:
        i. Population: raster_population_r_NER_FBpop2013_1km_final
        ii. Land cover merged: raster_land_cover_merged_r_NER_land_merged
        iii. Scenario table: table_scenario_walk_dry
        iv. Select existing health facilities layer (vector): v_NER_CSI_adj_barriers_1km
        v. ID field: id
        vi. Facility name field: nom_centre
        vii. Capacity: capacity
        viii. Select zones layer (vector): adm3
            1. Select zones unique ID (integer): objectid
            2. Select zone name (text): nom_com
    b. We used the following analysis settings:
        i. Type of analysis: anisotropic
        ii. Direction of travel: towards facilities
        iii. Facilities processing order according to: The population living within a given travel time from the facilities
            1. Travel time (minutes) for the processing order: 60
        iv. Processing order: Descending
        v. Maximum travel time (minutes): 60
        vi. Options
            2. Compute population catchment area layer: Yes
            3. Remove the covered population at each iteration: Yes
            4. Compute a layer of population cells on barriers: Yes
            5. Generate zonal statistics: Yes (adm 3)
            6. Run the analysis without considering capacities: No
            7. Add column with original population sum under each facility's travel time: Yes
            8. Optimize dynamically computation according to the scenario: Yes
            9. Add short tag: r_NER_gcCSI_60min_1km_prioritize_popAire

Variable "amPopCoveredPercent_TotalPop" in the tab "Pop_CSI" of Supplementary Appendix 3 provides the cumulative geographic coverage of the estimated total population covered by the CSI network. See Supplementary Appendix 1b at https://doi.org/10.5281/zenodo.4482969) for the vector shapefile (polygons) of the modelled catchment area of each CSI.

**Methods for Geographic Coverage research question 2**

We conducted a geographic coverage analysis of the estimated residual population beyond the geographic coverage of the existing CSI network in 2013 that were covered by the existing CS-ASC network in 2013, with each CS-ASC catchment defined by a maximum travel time of 60 min (walking or walking + motorized vehicle) and maximum population capacity of 2500.

Data analysis

1. We conducted a geographic coverage analysis for the existing CS-ASC network in 2013 considering maximum population capacity using the variable "capacity" (set at 2500 population per MOH norms) and processing order based the estimated residual population within a 60-minute catchment (walking) of each CS-ASC. This provided the final outputs for the analysis of geographic coverage for the existing CS-ASC network.
    a. We used the following data inputs:

i. Population: raster_population_residual_r_NER_gcCSI_60min_1km_prioritize_popAire
ii. Land cover merged: raster_land_cover_merged_r_NER_land_merged
iii. Scenario table: table_scenario_walk_dry
iv. Select existing health facilities layer (vector): v_NER_cells_at_100m_with_CS_or_ASC_adj_barriers_1km
v. ID field: id
vi. Facility name field: cat
vii. Capacity: capacity
viii. Select zones layer (vector): adm3
    1. Select zones unique ID (integer): objectid
    2. Select zone name (text): nom_com

b. We used the following analysis settings:
    i. Type of analysis: anisotropic
    ii. Direction of travel: towards facilities
    iii. Facilities processing order according to: The population living within a given travel time from the facilities
        1. Travel time (minutes) for the processing order: 60
    iv. Processing order: Descending
    v. Maximum travel time (minutes): 60
    vi. Options
        1. Compute population catchment area layer: Yes
        2. Remove the covered population at each iteration: Yes
        3. Compute a layer of population cells on barriers: Yes
        4. Generate zonal statistics: Yes (adm 3)
        5. Run the analysis without considering capacities: No
        6. Add column with original population sum under each facility's travel time: Yes
        7. Optimize dynamically computation according to the scenario: Yes
        8. Add short tag: r_NER_gc_Existing_CS_ASC_rPop13_60min_1km_prioritize_rPop13Aire

Variable "amPopCoveredPercent_ResidPopBeyondCSI" in the tab "Pop_CS-ASC" of Supplementary Appendix 3 provides the cumulative geographic coverage of the estimated residual population covered by the CS-ASC network. Variable "amPopCoveredPercent_TotalPop" in the tab "Pop_CS-ASC" of Supplementary Appendix 3 provides the cumulative geographic coverage of the estimated total population covered by the CS-ASC network. See Supplementary Appendix 1b at https://doi.org/10.5281/zenodo.4482969 for the vector shapefile (polygons) of the modelled catchment area of each CS-ASC.

**Methods for Geographic Coverage research question 3**

The zonal statistics from Geographic Coverage research question 2 defacto provide the geographic coverage of the combined CSI + CS-ASC network.

**Scaleup**

Research questions

1. How many community health workers are needed (and where) to optimally cover the population beyond the 1-hour catchment of the existing network of CS + ASC and CSI?

The MoPH in Niger has planned to scale-up RC in communities beyond 5km of CS or CSI to provide a standard package of preventive, promotive and curative services, including iCCM. We conducted a geographic coverage analysis to determine how many RC would be needed (and where) to optimally cover the estimated residual population beyond the geographic coverage of the existing CSI and CS-ASC networks in 2013, within a maximum travel time of 60 min walking from/to the RC and maximum population capacity of 1000 for each RC. This analysis aimed to provide information (or at least a methodology) that could be used to inform a rational scale-up of the RC that would maximize geographic coverage of the residual population beyond the geographic coverage of the CS-ASC and CSI networks in 2013.

**Methods for Scaleup research question 1**

Data preparation

1. Identification of potential RC sites for scaleup:
    a. Given the norm for the RC-to-population ratio is 1 per 1000, we used a 500 people as a minimum cutoff to identify cells for potential RC sites because it would be inefficient and impractical to place RC in all communities beyond the geographic coverage of the existing CS-ASC and CSI networks, regardless of population size. We used the "Raster calculator" tool in QGIS 3.12.0 to prepare a GeoTiff raster that identified cells from the residual population raster of the geographic coverage analysis of the existing CS-ASC network in 2013 [raster_population_residual_r_NER_gcCS_ASC_60min_1km_prioritize_rFB13TT] with greater than or equal to 500 people. Note that the cells identified here were also beyond the geographic coverage of the CSI network, since the geographic coverage analysis for the existing CS-ASC network used the residual population from the geographic coverage analysis of the existing CSI network as the input population dataset. This resulted in 3521 cells identified as potential RC sites for scaleup.
    b. We used the "Polygonize" tool in QGIS 3.12.0-Bucarești[13] to convert the Geotiff raster from step 1 to a vector shapefile of 3521 potential RC sites for scaleup [v_NER_scaleup_RC_rFB13TTge500_1km].

Analysis

1. We conducted a geographic coverage analysis of the estimated residual population beyond the geographic coverage of the existing CS-ASC network in 2013 (and defacto beyond the geographic coverage of the combined CSI + CS-ASC network) that were covered by a hypothetical network of RC in 2013, with each RC site catchment defined by a maximum travel time of 60 min (walking or walking + motorized vehicle) and total maximum population capacity set at 50000 using the variable "capacityN".
    a. We used the following data inputs:
        i. Population: raster_population_residual_r_NER_gcCS_ASC_60min_1km_prioritize_rPop13
        ii. Land cover merged: raster_land_cover_merged_r_NER_land_merged
        iii. Scenario table: table_scenario_walk_dry
        iv. Select existing health facilities layer (vector): v_NER_scaleup_RC_rFB13TTge500_1km
        v. ID field: id
        vi. Facility name field: cat
        vii. Capacity: capacityN
        viii. Select zones layer (vector): adm3
            1. Select zones unique ID (integer): objectid
            2. Select zone name (text): nom_com
    b. We used the following analysis settings:
        i. Type of analysis: anisotropic
        ii. Direction of travel: towards facilities
        iii. Facilities processing order according to: The population living within a given travel time from the facilities
            1. Travel time (minutes) for the processing order: 60
        iv. Processing order: Descending
        v. Maximum travel time (minutes): 60
        vi. Options
            1. Compute population catchment area layer: Yes
            2. Remove the covered population at each iteration: Yes
            3. Compute a layer of population cells on barriers: Yes

4. Generate zonal statistics: Yes (adm 3)
5. Run the analysis without considering capacities: No
6. Add column with original population sum under each facility's travel time: Yes
7. Optimize dynamically computation according to the scenario: Yes
8. Add short tag: r_NER_gcscaleup_RC_rFB13TTge500_60min_wd_1km_prioritize_rPop13

2. Estimation of the number of RC needed: We applied the ratio of 1 RC per 1000 population, using the variable "amPopCatchmentTotal", to derive the number of RC needed to cover the population within each RC catchment.

See Supplementary Appendix 4 for outputs of the scale-up analysis and Supplementary Appendix 1b at https://doi.org/10.5281/zenodo.4482969 for the vector shapefiles (polygons) of the modelled catchment areas of each RC in the scaled-up RC network.

**Targeting**

We assessed how well targeted the existing network of CS-ASC in 2013 was in terms of targeting a) the estimated residual population b) the estimated residual under-five deaths and c) the estimated residual *Pf* malaria cases beyond the catchment of the CSI network in 2013 compared to three hypothetical CS-ASC networks:

a. Hypothetical CS-ASC network that optimized geographic coverage of the estimated residual population beyond the catchment of the existing CSI network in 2013 by ordering the deployment (processing order) based on the estimated residual population in 2013 within the catchment area of a given CS-ASC, prioritizing catchments with higher estimated residual population over those with lower estimated residual population.
b. Hypothetical CS-ASC network that optimized geographic coverage of the estimated residual under-five deaths beyond the catchment of the existing CSI network in 2013 by ordering the deployment (processing order) based on the estimated residual under-five deaths in 2013 within the catchment area of a given CS-ASC, prioritizing catchments with higher estimated residual under-five deaths over those with lower estimated residual under-five deaths
c. Hypothetical CS-ASC network that optimized geographic coverage of the estimated residual *Pf* malaria cases among all ages (0-99 years) beyond the catchment of the existing CSI network in 2013 by ordering the deployment (processing order) based on the estimated residual *Pf* malaria cases among all ages (0-99 years) in 2013 within the catchment area of a given CS-ASC, prioritizing catchments with higher estimated residual *Pf* malaria cases over those with lower estimated residual *Pf* malaria cases.

Because we did not know the actual order or scale-up of the existing CS-ASC network and because we wanted to ensure a conservative estimate of the efficiency of geographical targeting, for the comparison of geographic coverage of the population (comparison a above) we assumed the prioritization order for the existing CS-ASC network based on the estimated residual population within a 60-minute catchment (walking) of an existing CS-ASC (as with the hypothetical network in a above). For comparison of geographic coverage of the estimated residual U5 deaths (comparison b above) we assumed the prioritization order for the existing CS-ASC network based on the estimated residual U5 deaths within a 60-minute catchment (walking) of an existing CS-ASC (as with the hypothetical network in b above). For comparison of geographic coverage of the estimated residual *Pf* malaria cases (comparison c above) we assumed the prioritization order for the existing CS-ASC network based on the estimated residual *Pf* malaria cases within a 60-minute catchment (walking) of an existing CS-ASC (as with the hypothetical network in c above). This is likely to overestimate the slope (efficiency) for the existing network and result in a conservative (underestimated) estimate of the efficiency gains of the hypothetical network over the existing network. This conservative approach to estimating the efficiency gains of geographical targeting of the hypothetical network over the existing network is justified given the absence of knowledge of the true criteria and/or factors that determined the scale-up order the existing network.

Research questions

1. How well targeted was the existing network of CS-ASC in 2013 in terms of geographic coverage of the estimated residual population beyond the catchment of the existing CSI network in 2013 compared to a hypothetical network of CS-ASC deployed to optimize geographic coverage of the residual estimated population?
2. How well targeted was the existing network of CS-ASC in 2013 in terms of geographic coverage of the estimated residual under-five deaths beyond the catchment of the existing CSI network compared to a hypothetical network of CS-ASC deployed to optimize geographic coverage of the estimated residual under-five deaths?
3. How well targeted was the existing network of CS-ASC in 2013 in terms of geographic coverage of the estimated residual *Pf* malaria cases among all ages (0-99 years) beyond the catchment of the existing CSI network compared to a hypothetical network of CS-ASC deployed to optimize geographic coverage of the estimated residual *Pf* malaria cases?

**Methods for Targeting research question 1**

Data preparation

1. Preparation of the GeoTiff for the estimated count of the residual population beyond the geographic coverage of the existing CSI network in 2013 [raster_population_residual_ r_NER_gcCS-ASC _60min_1km_prioritize_rpop13]:
    a. See Methods for Geographic Coverage research question 2, Data analysis, step 1

Data analysis

1. Geographic coverage analysis of the estimated residual population by the existing network of CS-ASC, prioritizing estimated residual population: See Methods for Geographic Coverage research question 2, Data analysis, step 1.
2. Geographic coverage analysis of the estimated residual population by the hypothetical network of CS-ASC, prioritizing estimated residual population: We conducted a geographic coverage analysis for the network of the 5796 potential CS-ASC sites in 2013 considering maximum population capacity (set at 2500 population per MOPH norms) and a descending processing order (highest to lowest) based on the residual estimated population beyond the CSI network in 2013 within each 60-minute catchment (walking scenario). This prioritized the deployment of CS-ASC according to the size (highest to lowest) of the estimated residual population in their 60-minute catchment. This provided the final outputs for the geographic coverage analysis for the hypothetical network of CS-ASC sites that prioritized geographic coverage of the estimated residual population.
    a. We used the following data inputs:
        i. Population: raster_population_residual_r_NER_gcCSI_60min_1km_prioritize_rFB13TT
        ii. Land cover merged: raster_land_cover_merged_r_NER_land_merged
        iii. Scenario table: table_scenario_walk_dry
        iv. Select existing health facilities layer (vector): v_NER_Targeting_Hypothetical_CS_ASC_sites_FB13TTge500_1km
        v. ID field: id
        vi. Facility name field: cat
        vii. Capacity: capacity
        viii. Select zones layer (vector): adm3
            1. Select zones unique ID (integer): objectid
            2. Select zone name (text): nom_com
    b. We used the following analysis settings:
        i. Type of analysis: anisotropic
        ii. Direction of travel: towards facilities
        iii. Facilities processing order according to: The population living within a given travel time from the facilities
            1. Travel time (minutes) for prioritization: 60
        iv. Processing order: Descending

v. Maximum travel time (minutes): 60
vi. Options
1. Compute population catchment area layer: Yes
2. Remove the covered population at each iteration: Yes
3. Compute a layer of population cells on barriers: Yes
4. Generate zonal statistics: Yes (adm 3)
5. Run the analysis without considering capacities: No
6. Add column with original population sum under each facility's travel time: Yes
7. Optimize dynamically computation according to the scenario: Yes
8. Add short tag: r_NER_gcTargeting_Hypothetical_rPop13_60min_1km_capacityN_prioritize_rPop13Aire

For outputs, see Supplementary Appendix 5, tabs "rPop13_Existing" and "rPop13_Hypothetical", in which the variable "amPopCoveredPercent" indicates the cumulative geographic coverage of the residual population. Supplementary Appendix 1b at https://doi.org/10.5281/zenodo.4482969 contains the vector shapefile (polygon) indicating the modelled catchment area of each health service delivery point.

3. Comparison of geographic coverage of the existing CS-ASC network and the hypothetical CS-ASC network: See tabs "rPop13_Existing", "rPop13_Hypothetical" and "Comparison_rPop13" in Appendix 6. We compared the percentage of the estimated residual population beyond the geographic coverage of the existing CSI network in 2013 that was covered by the existing network of CS-ASC (from Geographic Coverage research Question 2) with the percentage of the estimated residual population beyond the geographic coverage of the existing CSI network in 2013 that was covered by the hypothetical network of CS-ASC that prioritized the estimated residual population in the processing order (from Targeting research question 1, Data Analysis step 1 above) given the same number of potential CS-ASC sites as in the existing network of CS-ASC (i.e. 2550) as well as for the total number of potential CS-ASC sites (i.e. 5796).
   a. In tab "rPop13_Existing" of Supplementary Appendix 5, we sorted the results using variable "amPopCatchmentTotal" from highest to lowest, assuming maximal efficiency of the existing network. Maintaining this order, the last value for the variable "amPopCoveredPercent_ResidPopBeyondCSI" provided the percentage of the estimated population beyond the 1hr catchment of the existing CSI network in 2013 that was covered by the existing network of CS-ASC.
   b. In tab "rPop13_Hypothetical" of Supplementary Appendix 5, we sorted the results using variable "amPopCatchmentTotal" from highest to lowest, assuming maximal efficiency of the hypothetical network (as was done above for the existing network). Maintaining this order, the value for the variable "amPopCoveredPercent_ResidPopBeyondCSI" for the 2550$^{th}$ potential CS-ASC (distributed in 1523 1km locations) provided the percentage of the estimated population beyond the 1hr catchment of the existing CSI network in 2013 that was covered by the hypothetical network of CS-ASC that prioritized the residual population in the processing order, using the same number of sites as the existing CS-ASC network. The value for the variable "amPopCoveredPercent_ResidPopBeyondCSI" for the 5796$^{th}$ potential CS-ASC provided the percentage of the estimated population beyond the 1hr catchment of the existing CSI network in 2013 that was covered by the full hypothetical network of the 5796 CS-ASC, prioritizing the residual population in the processing order.
   c. In tab "Comparison_Population" of Supplementary Appendix 5, we compared the results from 3a for the network of existing CS-ASC to the results from 3b for the first 2550 hypothetical CS-ASC in terms of the absolute and relative difference in geographic coverage of the estimated residual population beyond the 60-minute catchment of the CSI network and estimated residual population covered beyond the 60-minute catchment of the CSI network.

**Methods for Targeting research question 2**

Data preparation

1. Preparation of the GeoTiff for the estimated count of residual under-five deaths beyond the geographic coverage of the existing CSI network
    a. See section I. Data inputs, Estimated under-five mortality for details.

Analysis

1. Geographic coverage analysis of the estimated residual under-five deaths by the existing network of CS-ASC: We conducted a geographic coverage analysis for the estimated residual under-five deaths beyond the geographic coverage of the existing CSI network, using the existing network of CS-ASC sites in 2013, with the processing order based on the capacity of the CS-ASC sites and setting the maximum population capacity (variable "CapacityN") at 100000 to effectively not consider maximum population capacity as a constraint to the CS-ASC catchment areas. The analysis removed the under-five deaths within each catchment area at each iteration (calculation of each catchment area) to avoid double counting under-five deaths where the 60 min catchment areas overlap. This provided the final outputs for the geographic coverage analysis for the existing CS-ASC network.
    a. We used the following data inputs:
        i. Population: r_NER_U5d13_final_1km
        ii. Land cover merged: raster_land_cover_merged_r_NER_land_merged
        iii. Scenario table: table_scenario_walk_dry
        iv. Select existing health facilities layer (vector): v_NER_cells_at_100m_with_CS_or_ASC_adj_barriers_1km
        v. ID field: id
        vi. Facility name field: cat
        vii. Capacity: capacityN
        viii. Select zones layer (vector): adm3
            1. Select zones unique ID (integer): objectid
            2. Select zone name (text): nom_com
    b. We used the following analysis settings:
        ix. Type of analysis: anisotropic
        x. Direction of travel: towards facilities
        xi. Facilities processing order according to: A field in the facility layer "capacity"
        xii. Processing order: Descending
        xiii. Maximum travel time (minutes): 60
        xiv. Options
            1. Compute population catchment area layer: Yes
            2. Remove the covered population at each iteration: Yes
            3. Compute a layer of population cells on barriers: Yes
            4. Generate zonal statistics: Yes (adm 3)
            5. Run the analysis without considering capacities: No
            6. Add column with original population sum under each facility's travel time: Yes
            7. Optimize dynamically computation according to the scenario: Yes
            8. Add short tag: r_NER_gc_Existing_CS_ASC_rU5d13_60min_1km_prioritize_rU5d13Aire
2. Geographic coverage analysis of the estimated residual under-five deaths by the hypothetical network of CS-ASC, prioritizing estimated residual under-five deaths in the processing order: We conducted a geographic coverage analysis for the estimated residual under-five deaths beyond the geographic coverage of the existing CSI network, using the hypothetical network of CS-ASC sites in 2013, with the processing order based on the estimated residual count of under-five deaths within each catchment "rU5d13" and setting the maximum population capacity at 100000 to effectively not consider maximum population capacity as a constraint to the CS-ASC catchment areas. The analysis removed the under-five deaths within each catchment area at each iteration (calculation of each catchment area) to avoid double counting under-five deaths where the 60 min catchment areas overlap. This provided the final outputs for the geographic coverage analysis for the optimized CS-ASC network, prioritizing deployment based on the estimated count of under-five deaths.

a. We used the following data inputs:
   i. Population: r_NER_U5d13_final_1km
   ii. Land cover merged: raster_land_cover_merged_r_NER_land_merged
   iii. Scenario table: table_scenario_walk_dry
   iv. Select existing health facilities layer (vector): v_NER_Targeting_Hypothetical_CS_ASC_sites_FB13TTge500_1km
   v. ID field: id
   vi. Facility name field: cat
   vii. Capacity: capacityN
   viii. Select zones layer (vector): adm3
      1. Select zones unique ID (integer): objectid
      2. Select zone name (text): nom_com
b. We used the following analysis settings:
   i. Type of analysis: anisotropic
   ii. Direction of travel: towards facilities
   iii. Facilities processing order according to: The population living within a given travel time from the facilities
      a. Travel time (minutes) for processing order: 60
   iv. Processing order: Descending
   v. Maximum travel time (minutes): 60
   vi. Options
      1. Compute population catchment area layer: Yes
      2. Remove the covered population at each iteration: Yes
      3. Compute a layer of population cells on barriers: Yes
      4. Generate zonal statistics: Yes (adm 3)
      5. Run the analysis without considering capacities: No
      6. Add column with original population sum under each facility's travel time: Yes
      7. Optimize dynamically computation according to the scenario: Yes
      8. Add short tag: r_NER_gcTargeting_Hypothetical_rU5d13_60min_1km_prioritize_rU5d13Aire

3. For outputs, see Supplementary Appendix 5, tabs "rU5d13_Existing" and "rU5d13_Hypothetical", in which the variable "amPopCoveredPercent" indicates the cumulative geographic coverage of the residual U5 deaths. Supplementary Appendix 1b at https://doi.org/10.5281/zenodo.4482969 contains the vector shapefile (polygon) indicating the modelled catchment area of each health service delivery point.
4. Comparison of geographic coverage of the existing CS-ASC network and the hypothetical CS-ASC network: See tabs "U5d_Existing", "U5d_Hypothetical" and "Comparison_U5deaths" in Supplementary Appendix 5. We compared the percentage of the estimated residual U5 deaths beyond the geographic coverage of the existing CSI network in 2013 that was covered by the existing network of CS-ASC, prioritizing the estimated residual population in the processing order, with the percentage of the estimated residual U5 deaths beyond the geographic coverage of the existing CSI network in 2013 that was covered by the hypothetical network of CS-ASC, prioritizing the estimated residual U5 deaths in the processing order given the same number of potential CS-ASC sites as in the existing network of CS-ASC (i.e. 2550). There is no MOPH norm for the ratio of ASC per U5 deaths and thereby no maximum capacity limit of the ASC for U5 deaths. Rather than make the unrealistic assumption that one CS-ASC could cover all U5 deaths within their catchment regardless of population size, we calculated the number of CS-ASC required in both the existing CS-ASC network and hypothetical CS-ASC network to completely cover (saturate) the estimated residual population in each catchment based on the MOPH ratio of one CS-ASC per 2500 population. For the existing CS-ASC network, this resulted in 2550 CS-ASC in 1924 CS-ASC catchments (see variable "rPop13Cum_CS-ASC_saturate" in the tab "rU5d13_Existing" in Supplementary Appendix 5). For the hypothetical CS-ASC network, this resulted in 2550 CS-ASC in 2044 CS-ASC catchments (see variable "rPop13Cum_CS-ASC_saturate" in the tab "rU5d13_Existing" in Supplementary Appendix 5).

a. In tab "rU5d13_Existing" of Supplementary Appendix 5, we sorted the results using variable "amPopCatchmentTotal" from highest to lowest, assuming maximal efficiency of the existing network. Maintaining this order, the value for the variable "amPopCoveredPercent_ResidPopBeyondCSI" for the 2550$^{th}$ CS-ASC (see cell see cell V1924 in tab "rU5d13_Existing) distributed in 1924 catchments provided the percentage of estimated U5 deaths beyond the 1hr catchment of the existing CSI network in 2013 that was covered by the existing network of 2550 CS-ASC.
b. In tab "rPop13_Hypothetical" of Supplementary Appendix 5, we sorted the results using variable "amPopCatchmentTotal" from highest to lowest, assuming maximal efficiency of the hypothetical network (as was done above for the existing network). Maintaining this order, the value for the variable "amPopCoveredPercent_ResidPopBeyondCSI" for the 2550$^{th}$ potential CS-ASC (see cell V2044 in tab "rU5d13_Hypothetical") distributed in 2044 catchments provided the percentage of the estimated U5 deaths beyond the 1hr catchment of the existing CSI network in 2013 that was covered by the hypothetical network of CS-ASC that prioritized the residual U5 deaths in the processing order, using the same number of CS-ASC as the existing CS-ASC network.
c. In tab "Comparison_U5deaths" of Supplementary Appendix 5, we compared the results from 3a for the network of existing CS-ASC to the results from 3b for the first 2550 hypothetical CS-ASC in terms of the absolute and relative difference in geographic coverage of the estimated residual U5 deaths beyond the 60-minute catchment of the CSI network and estimated number of U5 deaths covered beyond the 60-minute catchment of the CSI network.

Uncertainty analysis

We assessed the potential effect of uncertainty of the estimates for under-five deaths on targeting as follows. We used the "Zonal statistics" tool in QGIS 3.12.0-Bucarești[13] to extract the estimated mean and 95% confidence intervals for the number of under-five deaths for each catchment area defined by the geographic coverage analysis for the hypothetical network from step 2 of targeting research question 2. We sorted the catchments by the estimated mean number of under-five deaths from largest to smallest, as this reflected the prioritization order of the geographic coverage analysis used for the targeting analysis (step 2 of targeting research question 2). Because policy makers and planners typically support scale-up of facilities and CHWs in groups we identified five potential groups of CS-ASC for consideration. Group 1 included the 500 CS-ASC with the highest estimated mean number of under-five deaths, (median of means across catchments = 128, median of lower 95% confidence interval = 108, and median of upper 95% confidence interval = 149). Group 2 included 500 CS-ASC with the next highest estimated mean number of under-five deaths (median of means across catchments = 43, median of lower 95% confidence interval = 36, and upper 95% confidence interval = 51). Group 3 included 500 CS-ASC with next highest estimated mean number of under-five deaths (median of means across catchments = 24, median of lower 95% confidence interval = 20, and median of upper 95% confidence interval = 28). Group 4 included 500 catchments with the next highest mean number of under-five deaths (median of means across catchments = 16, median of lower 95% confidence interval minimum = 13, and median of upper 95% confidence interval = 19). Group 5 included 550 catchment CS-ASC with the next highest estimated mean number of under-five deaths (median of means across catchments = 11, median of lower 95% confidence interval = 9, median of upper 95% confidence interval = 13.0). Based on the medians of the 95% confidence intervals, decision makers could confidently prioritize Group 1 over Groups 2-5; Group 2 over Groups 3-5; Group 3 over Groups 4-5; and Group 4 over Group 5 (see Supplementary Appendix 5 – Targeting uncertainty, tabs "Summary_uncertainty_rU5d13" and "Groups_uncertainty_rU5d13").

**Methods for Targeting research question 3**

Data preparation

1. Preparation of the GeoTiff for the estimated count of residual *Pf* malaria cases among all ages (0-99 years): See section I. Data inputs, Estimated *Plasmodium falciparum* malaria cases

Analysis

1. Geographic coverage analysis of the estimated residual *Pf* malaria cases among all ages (0-99 years) by the existing network of CS-ASC: We conducted a geographic coverage analysis for the estimated residual *Pf* malaria cases (all ages) beyond the geographic coverage of the existing CSI network, using the existing network of CS-ASC sites in 2013, with the processing order based on the capacity of the CS-ASC sites, and setting the maximum population capacity (variable "CapacityN") at 100000 to effectively not consider maximum population capacity as a constraint to the CS-ASC catchment areas. The analysis removed the estimated *Pf* malaria cases (all ages) within each catchment area at each iteration (calculation of each catchment area) to avoid double counting estimated *Pf* malaria cases (all ages) where the 60 min catchment areas overlap. This provided the final outputs for the analysis of geographic coverage of the estimated residual under-five deaths by the existing CS-ASC network.
    a. We used the following data inputs:
        i. Population: r_NER_rCases13_final_1km
        ii. Land cover merged: raster_land_cover_merged_r_NER_land_merged
        iii. Scenario table: table_scenario_walk_dry
        iv. Select existing health facilities layer (vector): v_NER_cells_at_100m_with_CS_or_ASC_adj_barriers_1km
        v. ID field: id
        vi. Facility name field: cat
        vii. Capacity: capacityN
        viii. Select zones layer (vector): adm3
            1. Select zones unique ID (integer): objectid
            2. Select zone name (text): nom_com
    b. We used the following analysis settings:
        i. Type of analysis: anisotropic
        ii. Direction of travel: towards facilities
        iii. Facilities processing order according to: A field in the facility layer "capacity"
        iv. Processing order: Descending
        v. Maximum travel time (minutes): 60
        vi. Options
            1. Compute population catchment area layer: Yes
            2. Remove the covered population at each iteration: Yes
            3. Compute a layer of population cells on barriers: Yes
            4. Generate zonal statistics: Yes (adm 3)
            5. Run the analysis without considering capacities: No
            6. Add column with original population sum under each facility's travel time: Yes
            7. Optimize dynamically computation according to the scenario: Yes
        vii. Add short tag: r_NER_gc_Existing_CS_ASC_rCases13_60min_1km_prioritize_rCases13Aire
2. Geographic coverage analysis of the estimated residual *Pf* malaria cases among all ages (0-99 years) by the hypothetical network of CS-ASC, prioritizing estimated residual *Pf* cases in the processing order: We conducted a geographic coverage analysis for the estimated residual *Pf* malaria cases among all ages (0-99 years) beyond the geographic coverage of the existing CSI network, using the existing network of CS-ASC sties in 2013, with the processing order based on the estimated residual *Pf* malaria cases in 2013 within 60-minute of each CS-ASC site and setting the maximum population capacity at 100000 to effectively not consider maximum population capacity as a constraint to the CS-ASC catchment areas. The analysis removed the estimated *Pf* malaria cases within each catchment area at each iteration (calculation of each catchment area) to avoid double counting estimated *Pf* malaria cases where the 60 min catchment areas overlap. This provided the final outputs for the analysis of geographic coverage of the estimated residual under-five deaths by the existing CS-ASC network.
    a. We used the following data inputs:
        i. Population: r_NER_rCases13_final_1km
        ii. Land cover merged: raster_land_cover_merged_r_NER_land_merged
        iii. Scenario table: table_scenario_walk_dry

iv. Select existing health facilities layer (vector): v_NER_Targeting_Hypothetical_CS_ASC_sites_FB13TTge500_1km
v. ID field: id
vi. Facility name field: cat
vii. Capacity: capacityN
viii. Select zones layer (vector): adm3
    1. Select zones unique ID (integer): objectid
    2. Select zone name (text): nom_com

b. We used the following analysis settings:
    i. Type of analysis: anisotropic
    ii. Direction of travel: towards facilities
    iii. Facilities processing order according to: The population living within a given travel time from the facilities
        1. Travel time (minutes) for processing order: 60
    iv. Processing order: Descending
    v. Maximum travel time (minutes): 60
    vi. Options
        1. Compute population catchment area layer: Yes
        2. Remove the covered population at each iteration: Yes
        3. Compute a layer of population cells on barriers: Yes
        4. Generate zonal statistics: Yes (adm 3)
        5. Run the analysis without considering capacities: No
        6. Add column with original population sum under each facility's travel time: Yes
        7. Optimize dynamically computation according to the scenario: Yes
        8. Add short tag: r_NER_gcCS_ASC_rCases13_60min_1km_prioritize_rCases13Aire

For outputs, see Supplementary Appendix 5, tabs "rCases13_Existing" and "rCases13_Hypothetical", in which the variable "amPopCoveredPercent" indicates the cumulative geographic coverage of the residual population. Supplementary Appendix 1b at https://doi.org/10.5281/zenodo.4482969 contains the vector shapefile (polygon) indicating the modelled catchment area of each health service delivery point.

3. Comparison of geographic coverage of the existing CS-ASC network and the hypothetical CS-ASC network: We compared the percentage of the estimated residual *Pf* malaria cases among all ages (0-99 years) beyond the geographic coverage of the existing CSI network in 2013 that was covered by the existing network of CS-ASC, prioritizing the estimated residual population in the processing order, with the percentage of the estimated residual *Pf* malaria cases among all ages (0-99 years) beyond the geographic coverage of the existing CSI network in 2013 that was covered by the hypothetical network of CS-ASC, prioritizing the estimated residual *Pf* malaria cases among all ages (0-99 years) in the processing order given the same number of potential CS-ASC sites as in the existing network of CS-ASC (i.e. 2550). There is no MOPH norm for the ratio of ASC per *Pf* malaria cases and thereby no maximum capacity limit of the ASC for *Pf* malaria cases. Rather than make the unrealistic assumption that one CS-ASC could cover all *Pf* malaria cases within their catchment regardless of population size, we calculated the number of CS-ASC required in both the existing CS-ASC network and hypothetical CS-ASC network to completely cover (saturate) the estimated residual population in each catchment based on the MOPH ratio of one CS-ASC per 2500 population. For the existing CS-ASC network, this resulted in 2550 CS-ASC in 1893 CS-ASC catchments (see variable "rPop13Cum_CS-ASC_saturate" in the tab "rU5d13_Existing" in Supplementary Appendix 5). For the hypothetical CS-ASC network, this resulted in 2550 CS-ASC in 2044 CS-ASC catchments (see variable "rPop13Cum_CS-ASC_saturate" in the tab "rU5d13_Existing" in Supplementary Appendix 5).
    a. In tab "rCases13_Existing" of Supplementary Appendix 5, we sorted the results using variable "amPopCatchmentTotal" from highest to lowest, assuming maximal efficiency of the existing network. Maintaining this order, the value for the variable "amPopCoveredPercent_ResidPopBeyondCSI" for the 2550th CS-ASC (see cell see cell V1893 in tab "rCases13_Existing) distributed in 1893 catchments

provided the percentage of estimated *Pf* malaria cases (all ages) beyond the 1hr catchment of the existing CSI network in 2013 that was covered by the existing network of 2550 CS-ASC.

b. In tab "rCases13_Hypothetical" of Supplementary Appendix 5, we sorted the results using variable "amPopCatchmentTotal" from highest to lowest, assuming maximal efficiency of the hypothetical network (as was done above for the existing network). Maintaining this order, the value for the variable "amPopCoveredPercent_ResidPopBeyondCSI" for the 2550$^{th}$ potential CS-ASC (see cell V1553 in tab "rCases13_Hypothetical") distributed in 1553 catchments provided the percentage of the estimated *Pf* malaria cases beyond the 1hr catchment of the existing CSI network in 2013 that was covered by the hypothetical network of CS-ASC that prioritized the residual *Pf* malaria cases in the processing order, using the same number of CS-ASC as the existing CS-ASC network.
c. In tab "Comparison_Malaria" of Supplementary Appendix 5, we compared the results from 3a for the network of existing CS-ASC to the results from 3b for the first 2550 hypothetical CS-ASC in terms of the absolute and relative difference in geographic coverage of the estimated residual *Pf* malaria cases (all ages) beyond the 60-minute catchment of the CSI network and estimated number of *Pf* malaria cases (all ages) covered beyond the 60-minute catchment of the CSI network.

Uncertainty analysis

We assessed the potential effect of uncertainty of the estimates for under-five deaths on targeting as follows. We used the "Zonal statistics" tool in QGIS 3.12.0-Bucarești[13] to extract the estimated mean and 95% confidence intervals for the number of *Pf* malaria cases for all ages (0-99 years) for each catchment area defined by the geographic coverage analysis for the hypothetical network from step 2 of targeting research question 3. We sorted the catchments by the estimated mean number of *Pf* malaria cases for all ages (0-99 years) from largest to smallest, as this reflected the prioritization order of the geographic coverage analysis used for the targeting analysis (step 2 of targeting research question 3). Because policy makers and planners typically support scale-up of facilities and CHWs in groups we identified five potential groups of CS-ASC for consideration. Group 1 included 500 catchments with the highest estimated mean number of *Pf* malaria cases, (median of means across catchments = 12865, median of lower 95% confidence interval = 4568, and median of upper 95% confidence interval = 21303). Group 2 included 500 catchments with the next highest estimated mean number of *Pf* malaria cases (median of means across catchments = 3668, median lower 95% confidence interval = 1637, and median upper 95% confidence interval = 5414). Group 3 included 500 catchments with next highest estimated mean number of *Pf* malaria cases (median of means across catchments = 2417, median of lower 95% confidence interval = 1027, and median of upper 95% confidence interval = 3647). Group 4 included 500 catchments with the next highest mean number of *Pf* malaria cases (median of means across catchments = 1842, median of lower 95% confidence interval minimum = 824, and median of upper 95% confidence interval = 2738). Group 5 included 500 catchments with the next highest estimated mean number of *Pf* malaria cases (median of means across catchments = 1462, median of lower 95% confidence interval = 619, and median of upper 95% confidence interval = 2240). Based on the medians of the 95% confidence intervals, decision makers could confidently prioritize Group 1 over Groups 2-5; Group 2 over Groups 3-5; Group 3 over Groups 4-5; and Group 4 over Group 5 (see Supplementary Appendix 6 – Targeting uncertainty, tabs "Summary_uncertainty_rCases13" and "Blocks_uncertainty_rCases13").

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