Chapter 6

Spatial Analysis — Part 2

In the previous section we have created maps that show the locations of vaccination sites in rural and urban census tracts.

That required us to:

- filter spatial objects,
- identify and extract spatial feature based on their spatial relation to other spatial features, and
- map (visualize) these features.

In this section we expand our analysis and assess rural communities in a selected county in Maryland and Baltimore City for the potential presence of vaccination deserts. Per our definition, a low-income census tract qualifies as a vaccination desert if 33% of its area is outside a 0.5 mile (urban) or 10 mile (rural) range of the vaccination site (Section 1.1).

Conceptually we need to identify:

1. low-income census tracts that are outside of a certain range of a vaccination site, and
2. low-income tracts that have less than 33% of their area within the range of a vaccination site.

To identify these tracts, we need to further manipulate spatial objects, including:

- merge spatial features,
- buffer,
- clip, and
- perform simple mathematical operations on spatial features.

Before we continue, let us create a Maryland state boundary map and a map containing county boundaries. For the latter, read in the shapefile **`MD_counties_CT.shp`**. This map contains boundaries of the counties of Maryland. I created the file by extracting all counties from the census tract map (**`MD_CensusTracts_6487`**), and unifying the census tracts of each county. The Maryland state boundary map is created by unifying the census tracts of the entire state. The following script produces these maps that should look similar to the maps in Figure 6.1.

```
MD_counties <- st_read("data/MD_counties_CT.shp")

# draw Map (Fig. 6.1 A)
map_MD_counties <- tm_shape(MD_counties) +
                   tm_borders()

map_MD_counties

# create MD_state (Fig. 6.1 B)
MD_state <- st_union(MD_counties)

# draw Map
map_MD_state <- tm_shape(MD_state) +
                   tm_fill(col = "antiquewhite") +
                   tm_borders()

map_MD_state
```

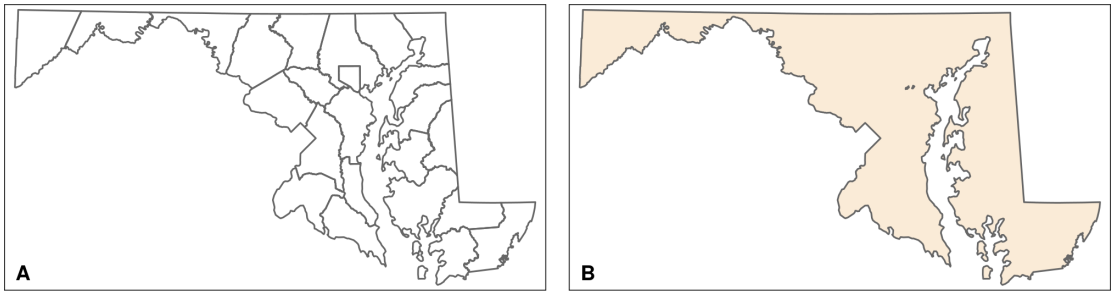

***FIGURE 6.1**. Map of political boundaries of Maryland, based on census tract boundaries. **A.** County boundaries. **B.** State boundaries.*

6.1 Identification of Possible Rural Vaccination Deserts

To identify areas with limited access to vaccination sites, we first create a 10-mile buffer around all Maryland vaccination sites (listed in **`VaccineSites_6487`**) with the function **`st_buffer()`**. The **`CRS`** of our maps uses meter. Thus, we need to convert miles to meter. One mile is approximately 1.690344 meters. Ten miles are therefore 16,093 meters, which is provided to the **`dist`** argument of **`st_buffer()`**. We join (unify) overlapping buffers with **`st_union()`**, and crop (clip) the ten mile ranges with **`st_intersection()`** to the state boundaries of Maryland.

```
# create a 10 mi buffer
vac_10mi <- st_buffer(VaccineSites_6487, dist = 1.609344*1e04)

# join/unify overlapping buffers
vac_10mi_union <- st_union(vac_10mi)

# clip/crop
vac_10mi_state <- st_intersection(MD_state, vac_10mi_union)
```

Next we plot Maryland's vaccination sites with the ten-mile buffer onto the counties "base map" (**map_MD_counties**). The **alpha** argument of the **tm_fill()** function sets a transparency level. One would mean no transparency (100% opacity), and zero 100% transparency (0% opacity). We set it to 65% (**alpha = 0.35**). The code produces a map similar to Figure 6.2.

```
# draw map
map_vac_10mi_md <- map_MD_counties +
                   tm_shape(vac_10mi_state) +
                   tm_fill(col = "orange",
                               alpha = 0.35) +
                   tm_borders(col = "red") +
                   map_VaccineSites

map_vac_10mi_md
```

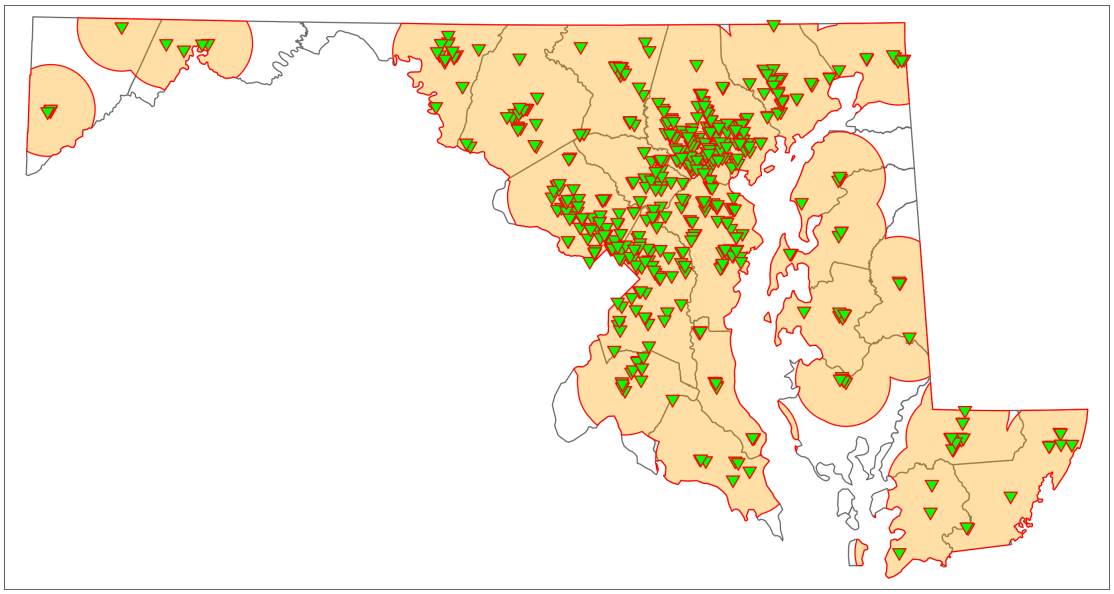

***FIGURE 6.2**. Vaccination sites with a 10 mi buffer, clipped to the Maryland state border.*

Now we identify low-income rural census tracts. We subset **MD_CensusTracts_6487** for **Urban == 0** and **LowIncomeTracts == 1**.

```
rural_LowIncome <- subset(MD_CensusTracts_6487, Urban == 0 & LowIncomeTracts == 1)

rural_LowIncome
```

```
## Simple feature collection with 55 features and 13 fields
## Geometry type: MULTIPOLYGON
## Dimension:     XY
## Bounding box:  xmin: 185230.9 ymin: 27801.06 xmax: 547910.5 ymax: 230941.9
## Projected CRS: NAD83(2011) / Maryland
## First 10 features:
##     CensusTract               GEO_ID STATE COUNTY  TRACT    NAME  LSAD
## 1   24001000100 1400000US24001000100    24    001 000100       1 Tract
## 2   24001000200 1400000US24001000200    24    001 000200       2 Tract
## 3   24001000300 1400000US24001000300    24    001 000300       3 Tract
## 15  24001001502 1400000US24001001502    24    001 001502   15.02 Tract
## 16  24001001503 1400000US24001001503    24    001 001503   15.03 Tract
## 20  24001001900 1400000US24001001900    24    001 001900      19 Tract
## 21  24001002000 1400000US24001002000    24    001 002000      20 Tract
## 23  24001002200 1400000US24001002200    24    001 002200      22 Tract
## 299 24005451900 1400000US24005451900    24    005 451900    4519 Tract
## 353 24009860702 1400000US24009860702    24    009 860702 8607.02 Tract
##     CENSUSAREA    County Urban POP2010 LowIncomeTracts HUNVFlag
## 1      187.937  Allegany     0    3718               1        0
## 2       48.067  Allegany     0    4564               1        0
## 3        8.656  Allegany     0    2780               1        0
## 15       9.148  Allegany     0    2055               1        0
## 16      11.539  Allegany     0    1968               1        0
## 20      24.855  Allegany     0    2623               1        0
## 21      26.800  Allegany     0    5552               1        1
## 23      23.497  Allegany     0    3874               1        0
## 299      5.187 Baltimore     0    2445               1        0
## 353      9.430   Calvert     0    2974               1        0
##                           geometry
## 1   MULTIPOLYGON (((277992.7 21...
## 2   MULTIPOLYGON (((252677.1 22...
## 3   MULTIPOLYGON (((252464.7 22...
## 15  MULTIPOLYGON (((243626.5 22...
## 16  MULTIPOLYGON (((241785.2 22...
## 20  MULTIPOLYGON (((234463.9 22...
## 21  MULTIPOLYGON (((241888.4 21...
## 23  MULTIPOLYGON (((231767.6 19...
## 299 MULTIPOLYGON (((456497.8 17...
## 353 MULTIPOLYGON (((434677 1017...
```

There are 55 census tracts that qualify. The code below plots these tracts onto the map (Figure 6.3).

```
map_Rural_LowIncome_md <- map_MD_counties +
                          tm_shape(rural_LowIncome) +
                          tm_fill(col = "red",
                                  alpha = 0.75) +
                          tm_shape(vac_10mi_state) +
                          tm_fill(col = "orange",
                                  alpha = 0.5) +
                          tm_borders(col = "blue") +
                          map_VaccineSites

map_Rural_LowIncome_md
```

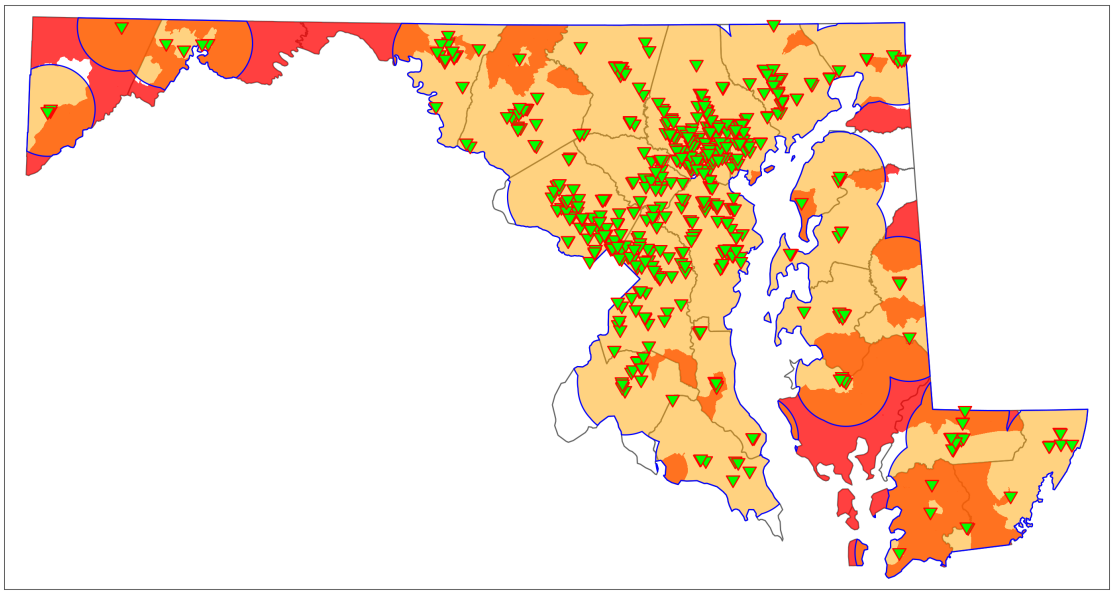

***FIGURE 6.3**. Rural low-income tracts and vaccination sites with a 10 mi buffer, clipped to the Maryland state border.*

We can narrow down the rural regions that may contain vaccination deserts by identifying rural low-income areas that are outside the 10-mile range of a vaccination site. The function **`st_difference()`** clips features that do not intersect with other features or are within other features. (Note that the code may produce a warning that can be ignored). The resulting plot should be similar to Figure 6.4. It shows rural areas (not census tracts) that would have limited access to vaccination sites in "hot pink." They are mainly located on the Eastern Shore (parts of Dorchester, Queen Anne's, and Kent County) and in Western Maryland (parts of Washington, Allegany, and Garrett County).

```
rural_vac_desert <- st_difference(rural_LowIncome, vac_10mi_state)

map_Rural_vac_desert <- map_MD_counties +
                        tm_shape(rural_vac_desert) +
                        tm_fill(col = "hotpink",
                                alpha = 0.75) +
                        tm_shape(vac_10mi_state) +
                        tm_fill(col = "orange",
                                alpha = 0.5) +
                        tm_borders(col = "blue") +
                        map_VaccineSites

map_Rural_vac_desert
```

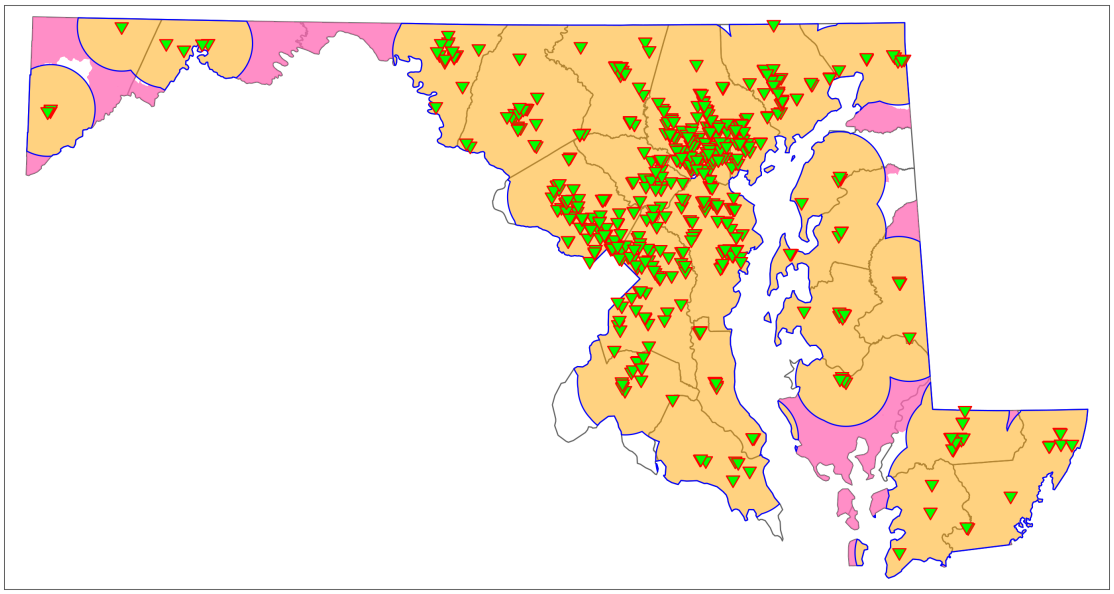

***FIGURE 6.4**. The map shows rural areas with potential vaccination deserts (highlighted in "hot pink").*

6.2 Possible Vaccination Deserts in Garrett County

The analysis above suggests that Garrett County in Western Maryland may have rural vaccination deserts, which warrants further analysis. Before we continue, we create a basemap for Garrett County that allows us to map possible vaccination deserts in Garrett County. The code below extracts Garrett County from **`MD_CensusTracts_6487`** using the **`County`** variable. It unifies the census tracts and plots a map. The plot should look similar to Figure 6.5 A.

```
Garrett_CensusTracts <- subset(MD_CensusTracts_6487, County == "Garrett")

Garrett_CensusTracts

Garrett_County <- st_union(Garrett_CensusTracts)

map_Garrett <- tm_shape(Garrett_County) +
               tm_fill(col = "antiquewhite") +
               tm_borders(col = "black")

map_Garrett
```

Next, we extract and map rural low-income tracts, that are highlighted in red. For reference, all census tracts are outlined (Figure 6.5 B).

```
Garrett_RuralLowIncome <- subset(Garrett_CensusTracts,
                                 Urban == 0 & LowIncomeTracts == 1)
Garrett_RuralLowIncome

map_Garrett_RuralLowIncome <- map_Garrett +
                              tm_shape(Garrett_CensusTracts) +
                              tm_borders(col = "black") +
                              tm_shape(Garrett_RuralLowIncome) +
                              tm_fill(col = "orange") +
                              tm_borders(col = "black")

map_Garrett_RuralLowIncome
```

Five of the seven census tracts in Garrett County qualify as rural low-income tracts. Next, we identify vaccination sites located in Garrett County. To identify areas with limited access to these sites we create again a 10-mile buffer around the Garrett County vaccination sites, join overlapping buffers, and clip the 10-mile buffers to the boundaries of Garrett County. For reference we label the tracts with their names (listed in the variable **NAME**) (Figure 6.5 C).

```
# Identify vaccination sites
vac_Garrett <- st_intersection(VaccineSites_6487, Garrett_County)

# Create a 10 mile buffer around vaccination sites
vac_Garrett_10mi <- st_buffer(vac_Garrett, dist = 1.690344*1e04)

# unify
vac_Garrett_10mi <- st_union(vac_Garrett_10mi)

# Clip to Garrett County Boundaries
vac_Garrett_10mi_clipped <- st_intersection(Garrett_County, vac_Garrett_10mi)
```

```
# map
# Garrett County Vaccine Sites
map_vac_Garrett <- tm_shape(vac_Garrett) +
                   tm_symbols(shape = 25,
                              size = 0.75,
                              col = "green",
                              border.col = "red")

map_Garrett_RuralLowIncome_10mi <- map_Garrett_RuralLowIncome +
                                   tm_shape(vac_Garrett_10mi_clipped) +
                                   tm_fill(col = "purple",
                                           alpha = 0.5) +
                                   map_vac_Garrett
map_Garrett_RuralLowIncome_10mi
```

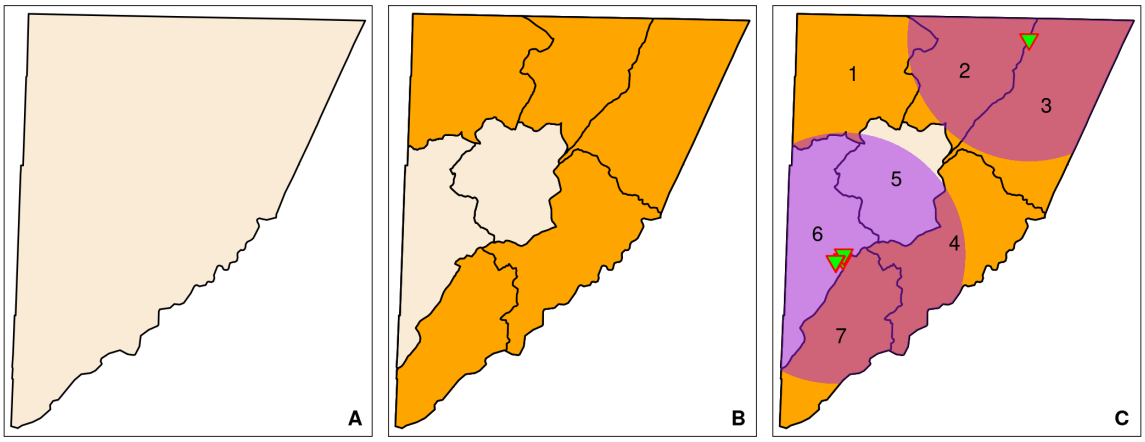

***FIGURE 6.5**. Maps of Garrett County. **A.** County boundaries. **B.** Rural low-income census tracts (highlighted in orange). **C.** Rural low-income census tracts (highlighted in orange) and ranges of vaccination sites (highlighted in purple). Location of vaccination sites are shown as green inverted triangles.*

Garrett County has five rural low-income tracts: tracts 1–4, and tract 7. Tracts 2–4 and 7 have large areas that are within the range of a vaccination site. Tract 1 has only two small sections that are within the range (Figure 6.5 C).

As discussed in Section 1.1, a low-income census tract should have at least 33% of its area outside of the range of a vaccination site to be flagged as a possible vaccination desert. Remember however that this definition has its limitations. It suggests that residential housing is evenly distributed throughout the census tract. This is likely not true for many rural areas.

Regardless, let's determine the relative sizes of the low-income census tracts sections that are outside of the range of a vaccination site. To do so, we first identify the sections that are within the range of a vaccination site, and determine their sizes. We use **`st_intersection()`** to extract the portions of the census tracts that is within the range of a vaccination site. Note that the low-income census tracts are listed first, followed by the 10-mile vaccination site buffer. Also, **`st_intersection()`** will

issue a warning that can be ignored. The resulting spatial object is assigned to **vac_assess**. Next, we calculate the area of the spatial features with **st_area()** (and assign the outcome to **vac_access_area**). Then we calculate the total area of the low-income census tracts (**st_area(Garrett_RuralIncome)**) and assign the output to the object **Garrett_RuralLowIncome_area**.

Since all five low-income tracts of Garrett County overlap with the 10-mile range of a vaccination site, we can calculate the relative area of a low-income tract that is outside the reach of a vaccination site by dividing **vac_access_area** by **Garrett_RuralLowIncome_area**. The quotient (result of the division) is converted into a vector (function **as.vector()**) and subtracted from one. The final ratio is assigned to a new variable (**outside_range_ratio**) to the **Garrett_RuralLowIncome_vac_area** created beforehand.

```
# determine region within range
vac_access <- st_intersection(Garrett_RuralLowIncome, vac_Garrett_10mi)
```

```
## Warning: attribute variables are assumed to be spatially constant throughout all
## geometries
```

```
vac_access_area <- st_area(vac_access)

vac_access_area
```

```
## Units: [m^2]
## [1]  21235139 190265302 267057684 137166602 177668272
```

```
# calcualting total area of each census tract (low income)
Garrett_RuralLowIncome_area <- st_area(Garrett_RuralLowIncome)

Garrett_RuralLowIncome_area
```

```
## Units: [m^2]
## [1] 275216882 208291591 323333623 268461042 214505992
```

```
# copy Garrett_RuralLowIncome
Garrett_RuralLowIncome_vac_area <- Garrett_RuralLowIncome

# Calculate area outside of the range
Garrett_RuralLowIncome_vac_area$outside_range_ratio <-
1 - as.vector(vac_access_area/Garrett_RuralLowIncome_area)

Garrett_RuralLowIncome_vac_area
```

```
## Simple feature collection with 5 features and 14 fields
## Geometry type: MULTIPOLYGON
## Dimension:     XY
## Bounding box:  xmin: 185230.9 ymin: 173522.8 xmax: 234427.1 ymax: 230941.9
## Projected CRS: NAD83(2011) / Maryland
##     CensusTract               GEO_ID STATE COUNTY  TRACT NAME  LSAD CENSUSAREA
## 530 24023000100 1400000US24023000100    24    023 000100    1 Tract    105.372
## 531 24023000200 1400000US24023000200    24    023 000200    2 Tract     80.293
## 532 24023000300 1400000US24023000300    24    023 000300    3 Tract    124.156
## 533 24023000400 1400000US24023000400    24    023 000400    4 Tract    102.178
## 536 24023000700 1400000US24023000700    24    023 000700    7 Tract     82.476
##      County Urban POP2010 LowIncomeTracts HUNVFlag
## 530 Garrett     0    4003               1        1
## 531 Garrett     0    3937               1        1
## 532 Garrett     0    2857               1        0
## 533 Garrett     0    3337               1        0
## 536 Garrett     0    5726               1        1
##                           geometry outside_range_ratio
## 530 MULTIPOLYGON (((187332 2221...          0.92284216
## 531 MULTIPOLYGON (((202819.1 23...          0.08654353
## 532 MULTIPOLYGON (((222190.9 20...          0.17404914
## 533 MULTIPOLYGON (((205719.8 18...          0.48906329
## 536 MULTIPOLYGON (((197757.6 18...          0.17173283
```

We then extract low-income tracts with an **`outside_range_ratio`** larger than 33% (0.33), which represent possible vaccination deserts.

```
# subset for vaccination deserts
Garrett_RuralVacDeserts <- subset(Garrett_RuralLowIncome_vac_area,
                                  outside_range_ratio > 0.33)

Garrett_RuralVacDeserts
```

```
## Simple feature collection with 2 features and 14 fields
## Geometry type: MULTIPOLYGON
## Dimension:     XY
```

```
## Bounding box:  xmin: 186998.7 ymin: 183652.7 xmax: 222098.7 ymax: 230941.9
## Projected CRS: NAD83(2011) / Maryland
##     CensusTract               GEO_ID STATE COUNTY  TRACT NAME  LSAD CENSUSAREA
## 530 24023000100 1400000US24023000100    24    023 000100    1 Tract    105.372
## 533 24023000400 1400000US24023000400    24    023 000400    4 Tract    102.178
##      County Urban POP2010 LowIncomeTracts HUNVFlag
## 530 Garrett     0    4003               1        1
## 533 Garrett     0    3337               1        0
##                           geometry outside_range_ratio
## 530 MULTIPOLYGON (((187332 2221...           0.9228422
## 533 MULTIPOLYGON (((205719.8 18...           0.4890633
```

```
# map
map_Garrett_RuralVacDeserts <- map_Garrett +
                               tm_shape(Garrett_CensusTracts) +
                               tm_borders(col = "black") +
                               tm_shape(Garrett_RuralLowIncome) +
                               tm_polygons(col = "orange") +
                               tm_shape(Garrett_RuralVacDeserts) +
                               tm_polygons(col = "red") +
                               map_vac_Garrett +
                               tm_add_legend(type = "symbol",
                                         shape = c(22, 22, 25),
                                         size = c(0.9, 0.9, 0.65),
                                         col = c("orange", "red", "green"),
                                         border.col = c("black", "black", "red"),
                                         label = c("Rural Low-income Tract",
                                                   "Potential Vaccination Desert",
                                                   "COVID-19 Vaccination Site")) +
                              tm_legend(position = c(0.65, 0.02),
                                        width = 0.6) +
                              tm_layout(legend.text.size = 0.85)

map_Garrett_RuralVacDeserts

#save map
tmap_save(map_Garrett_RuralVacDeserts,
          filename = "figures/map_Garrett_RuralVacDeserts.png")
```

Note that you may need to adjust the position of the legend manually for the saved file. I adjusted the legend position as follows to save the map to my liking (just replace the lines containing the **`tm_legend(position ...)`**).

```
tm_legend(position = c(0.65, 0.02),
                      width = 0.6) +
```

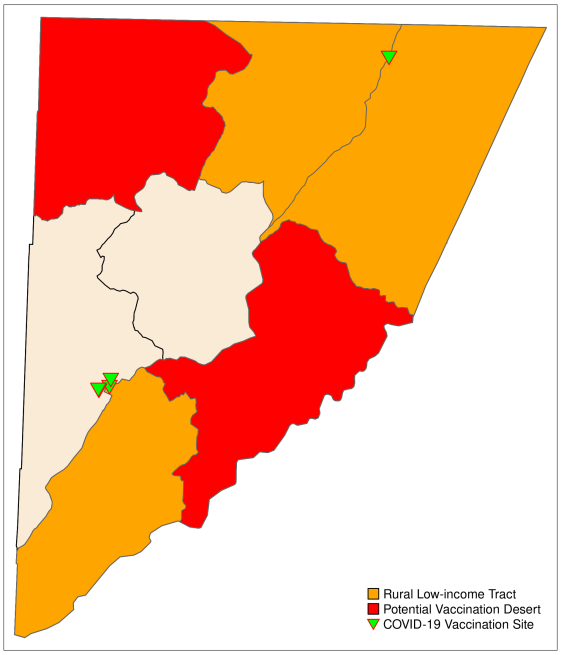

***FIGURE 6.6**. Map of Garrett County showing rural low-income census tracts (highlighted in red) that are potential vaccination deserts.*

6.3 Possible Vaccination Deserts in Baltimore City

We can use a similar approach to assess whether Baltimore City has "COVID-19 Vaccination Deserts." Of course, there are some modifications necessary.

- Remember, in an urban setting, we defined a limited-access census tract as a census tract where more than 33% of the area is outside of a 0.5 mile range to a vaccination site (0.5 mile is roughly 800 m). Thus, instead of creating a 10-mile buffer around vaccination sites, we create a 0.5 mile (800 m) buffer.
- Baltimore City is surrounded by other (Maryland) counties, in which Baltimore City residents can get vaccinated. Therefore, vaccination sites will be clipped to Baltimore City limits that are "expanded" by 800 m.
- As you will see, in contrast to Garrett County, Baltimore City has low-income tracts that are outside of the 0.5 miles range of vaccination sites (Figure 6.7 C), which we have to account for.

The first steps (up to mapping low-income tracts and buffered vaccination sites) in general follow the example we used for Garrett County:

1. We create a base map for Baltimore City and a map showing census tracts.
2. We extract low-income tracts and double check that we only have urban tracts.
3. We create a 800 m buffer around Baltimore City limits and identify vaccination sites that are within the extended Baltimore City limits.
4. We create a 800 m buffer around the vaccination sites and clip the buffered sites to the city limits (for aesthetics).
5. We plot Baltimore City's census tracts, low-income census tracts, and buffered vaccination sites.

```
# Create Baltimore City map
# From Census Tract Map
BC_CensusTracts <- subset(MD_CensusTracts_6487, County == "Baltimore City")

# Baltimore City outline
BC <- st_union(BC_CensusTracts)

# Map BC (Figure 6.7 A)

map_BC <- tm_shape(BC) +
          tm_fill(col = "antiquewhite") +
          tm_borders(col = "black")

map_BC
```

```
# Extract low income census tracts.
# check if non urban tracts are present.
subset(BC_CensusTracts, Urban == 0)  # just to be sure
```

```
## Simple feature collection with 0 features and 13 fields
## Bounding box:  xmin: NA ymin: NA xmax: NA ymax: NA
## Projected CRS: NAD83(2011) / Maryland
##  [1] CensusTract     GEO_ID          STATE           COUNTY
##  [5] TRACT           NAME            LSAD            CENSUSAREA
##  [9] County          Urban           POP2010         LowIncomeTracts
## [13] HUNVFlag        geometry
## <0 rows> (or 0-length row.names)
```

```
# <0 rows>, we are good to go
# Extract LowIncomeTracts
BC_LowIncome <- subset(BC_CensusTracts, LowIncomeTracts == "1")

# Map census tracts, highlight low-income census tracts orange (Fig. 6.7 B)
map_BC_LowIncome <- map_BC +
                    tm_shape(BC_CensusTracts) +
                    tm_borders(col = "black") +
                    tm_shape(BC_LowIncome) +
                    tm_fill(col = "orange") +
                    tm_borders(col = "black")

map_BC_LowIncome
```

```
# Create 800 m buffer for Baltimore City
BC_800m <- st_buffer(BC, dist = 800)

# Identify Vaccination Sites in BC (for mapping sites); ignore warning
vac_BC <- st_intersection(VaccineSites_6487, BC)

# Identify Vaccination Sites within "expanded" City; ignore warning
vac_BC_ext <- st_intersection(VaccineSites_6487, BC_800m)

# Create 0.5 mi (800m) buffer
vac_BC_800m <- st_buffer(vac_BC_ext, dist = 800)

# Unify
vac_BC_800m <- st_union(vac_BC_800m)

# Clip to BC boundaries (NOT BC_800m)
vac_BC_800m_clipped <- st_intersection(BC, vac_BC_800m)

# Map Vaccination Sites and buffer, only map sites in the city (Figure 6.7 C)
map_vac_BC <- tm_shape(vac_BC) +
              tm_symbols(shape = 25,
                         size = 0.5,
                         col = "green",
                         border.col = "black")

# map (figure 6.7 C)
map_BC_LowIncome_800m <- map_BC_LowIncome +
                         tm_shape(vac_BC_800m_clipped) +
                         tm_fill(col = "purple",
                                 alpha = 0.5) +
                         map_vac_BC

map_BC_LowIncome_800m
```

The **R** script produces maps similar to the plots in Figure 6.7 A–C. Indeed, Baltimore City has quite a few low-income tracts that are outside the 0.5 mile range of vaccination sites. These by definition are possible vaccination deserts. We need to separate them from the low-income tracts that are within the range of vaccination sites. Otherwise, we cannot calculate the area that overlap. The package **dplyr** has the function **anti_join()** that removes rows of a data frame if the rows are present in another data frame. However, the function does not work with 2 **sf** objects. The 2nd object needs to be a non spatial data frame.

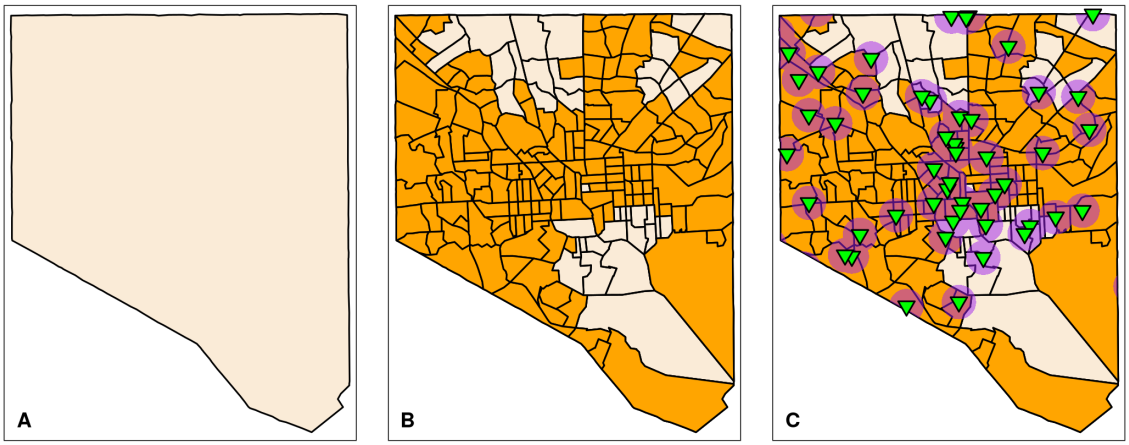

FIGURE 6.7*. Maps of Baltimore City.* ***A.*** *Outline of Baltimore City.* ***B.*** *Low-income census tracts (highlighted in orange).* ***C.*** *Low-income census tracts (highlighted in orange) and a range of vaccination sites (highlighted in purple). Location of vaccination sites are shown as green inverted triangles.*

To separate the low-income tracts that share some area with the buffered vaccination sites, we use the following approach.

1. We identify the area of the census tracts that overlap with the buffered vaccination site and name these **BC_vac_access**. We are using the function **st_intersection()**. As the function name implies, a spatial data frame is returned that only contains the intersection of both the census tracts and the buffered vaccination sites (Figure 6.8 A).

2. We obtain the tracts that do not overlap (the "no-access" tracts) by removing the tracts with access from the overall low-income tracts with the function **dplyr::anti_join()**. This possible because in **sf** objects the function **st_intersection()** does not alter non spatial information.

3. We obtain the entire census tracts that overlap with the buffered vaccination sites. We assign these tracts to the object **BC_withvac_access**.

The following **R** scripts produces a few plots that visualize the above process. The plots are shown in Figure 6.8 A–C. **st_intersection()** will again give warnings that can be ignored.

```
#=====================================================
# Step 1: identify the area that overlaps
#=====================================================

BC_vac_access <- st_intersection(BC_LowIncome, vac_BC_800m_clipped)

# Map BC_vac_access (Fig. 6.8 A)
# create an outline of Low Access census tracts
BC_LowIncome_outline <- st_union(BC_LowIncome)

# base map
BC_LI <- tm_shape(BC_LowIncome_outline) +
      tm_borders(col = "darkorange3",
                 lwd = 1.5) +
      tm_shape(BC_LowIncome_outline) +
      tm_fill(col = "antiquewhite") +
      tm_borders(col = "darkorange3",
                 lwd = 1.5)

map_BC_vac_access <- BC_LI +
      tm_shape(BC_vac_access) +  # area of overlap
      tm_fill(col = "purple",
              alpha = 0.25) +
      tm_borders(col = "darkblue")

map_BC_vac_access

#=====================================================
# Step 2: identify census tracts that do not overlap
#=====================================================

# Remove geometries from BC_vac_access
# drop spatial information from overlap (BC_vac_access
BC_vac_access_nsp <- st_drop_geometry(BC_vac_access)

BC_novac_access <- dplyr::anti_join(BC_LowIncome, BC_vac_access_nsp, by = "NAME")

# Map BC_novac_access (Fig. 6.8 B)
map_BC_novac_access <- BC_LI +
    tm_shape(BC_novac_access) + # tracts w/ no access
    tm_polygons(col = "red")

map_BC_novac_access

#=============================================
# Step 3 get census tracts with access (overlap)
#=============================================

# Remove geometries from BC_novac_access
BC_novac_access_nsp <- st_drop_geometry(BC_novac_access)

# Remove no-access from low-income tract
```

```
BC_withvac_access <- dplyr::anti_join(BC_LowIncome, BC_novac_access_nsp, by = "NAME")

# Map BC_withvac_access (Fig. 6.8 C)
map_BC_withvac_access <- BC_LI +
            tm_shape(BC_withvac_access) +
            tm_fill(col = "orange",
                    alpha = 0.5) +
            tm_borders(col = "darkorange3")

map_BC_withvac_access
```

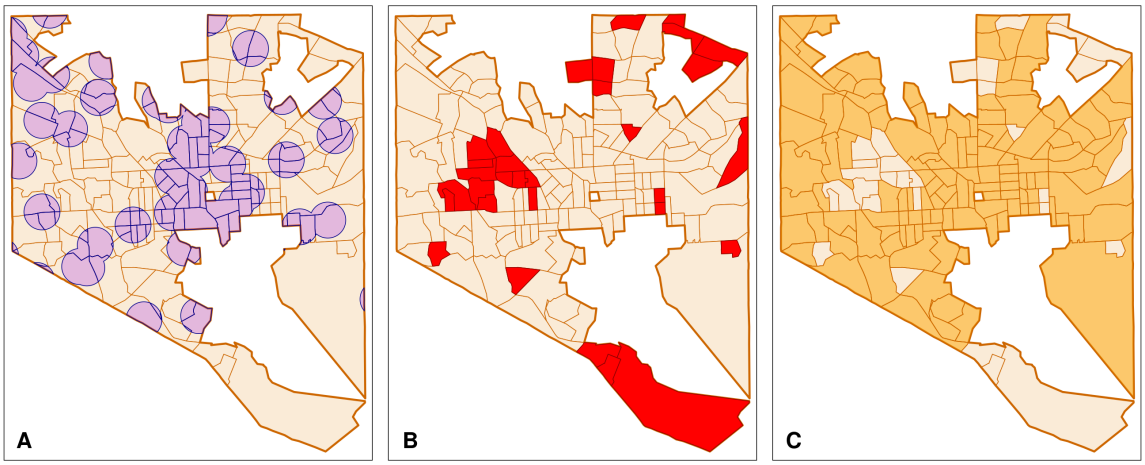

***FIGURE 6.8**. Outcome of spatial manipulations on low-income tracts of Baltimore City. **A.** Intersection of low-income tracts and buffered vaccination sites (highlighted in purple) generated by* **`st_intersection()`**. ***B.** Low-income tracts outside of the 0.5 mi buffer around vaccination sites ("no-access" low-income tracts; highlighted in red). **C.** Low-income census tracts that intersect with the vaccination site buffer ("with-access" low-income tracts; highlighted in orange).*

We have two sets of complete low-income census tracts: (1) census tracts that do not overlap ("no-access" low-income tracts; Figure 6.8 B), and (2) those that have areas within the 0.5 mile range to vaccination sites ("with-access" low-income tracts; Figure 6.8 C). These data sets allow us to calculate the portion of the area of a low-income tract that overlaps with the 0.5 mile buffer around vaccination sites. For these calculations it is important that the census tracts in both data frames (**`BC_vac_access`** and **`BC_withvac_access`**) are in the same order. To verify, we use the function **`identical()`**. It tests if two objects are exactly the same. We cannot compare the entire data frames since the geometry columns of the data frames differ. Furthermore, **`anti_join()`** from the **`dplyr`** package unfortunately does not preserve the row numbers. Instead we compare the entries in the variable **`GEO_ID`** as it is unique to each tract.

```
# check if NAME viable is the same in both data frames
identical(BC_vac_access$GEO_ID, BC_withvac_access$GEO_ID)
```

```
## [1] TRUE
```

TRUE is returned, confirming that in both data sets the order of the census tracts is identical. We now identify possible low-income tracts with limited-access to vaccination sites following the example of Garrett County. We first divide the area of the intersection (**BC_vac_access**) by the total area of the tract (**BC_withvac_access**), then subtract the quotient from 1, and lastly extract tracts that share no more than 33% with the buffer around vaccination sites.

```
# calculate area of the portions that are within the 0.5 mile range
BC_vac_access_area <- st_area(BC_vac_access)

BC_vac_access_area
```

```
## Units: [m^2]
##   [1]  426051.567  595722.353 1204742.968  437131.380    1595.308   68083.216
##   [7]  420835.141  133338.221  225786.014  326691.483   15006.228  281497.037
##  [13]  247188.754   74697.281   38425.821  202105.805  291927.929  251092.218
##  [19]  282982.776  327353.482   53235.925  128529.689  534636.724  291398.885
##  [25]  354049.787   87394.618  787116.713  544379.226   91860.517  204809.073
##  [31]  308259.900  706061.179  356875.579  934568.962  408658.063  270852.756
##  [37]  382688.840  503295.282 1020097.808   24903.375  318708.773   26947.737
##  [43]    8289.565  507238.123  293322.753  314815.420  593204.994  316978.938
##  [49]  259617.680  438479.266  298329.823  783814.209  681257.558   97632.114
##  [55]  875160.584  143299.770   12652.807   70685.473   46630.607  276051.933
##  [61]  484918.575  283264.985  340923.971  177094.232  160975.836  248396.176
##  [67]   92184.117  271324.877  265150.352  386301.387  207259.904  240586.509
##  [73]  180069.772 1248149.304   92392.360  130851.261  481958.333  989663.497
##  [79]    3416.019  292827.299   74827.221 1723568.441 1051350.778   29350.392
##  [85] 1186969.701  541803.150  407432.500   90406.402   44231.254  662949.100
##  [91] 1248459.714  173237.048  671154.321  130106.429  606352.391  536479.279
##  [97]   10152.565  423422.520  648875.862 1576870.203  171886.689  730677.745
## [103]  311145.862   84521.796  481436.695  801923.164  783199.034  575371.412
## [109]   62320.814   94295.486  305834.031   42781.522  753480.037  940759.662
## [115]  401882.661   46069.995  418841.769  294534.122  426904.915  758439.728
## [121] 1306801.799 2602953.864 1175111.918 1363236.743  113529.070  854045.245
## [127]  228777.089  408589.497  480149.958  924871.056
```

```
# Calculate total area of each low-income census tracts that intersect with a buffer
BC_withvac_access_area <- st_area(BC_withvac_access)

BC_withvac_access_area
```

```
## Units: [m^2]
##   [1]   427345.4   595722.4  1204743.0   437131.4   257719.1   186938.5
##   [7]   429559.1   314502.5   225786.0   326691.5  2299202.9   364736.1
##  [13]   863578.2   268338.1   440547.7   251437.0   350511.1   336465.9
##  [19]   298794.8   327485.2   659655.6  2031460.0   795632.8   350196.9
##  [25]   744957.2   446013.3   844748.8   685535.9   453673.4   304861.7
##  [31]   308259.9   706061.2   356875.6   991486.1   408658.1   270852.8
##  [37]   532064.0   503295.3  1040072.6   298538.9   362711.1   357715.6
##  [43]  2825307.7   904919.4   679703.3   718015.6   593205.0   395240.6
##  [49]   391087.0  1090207.3  1455134.1  1489384.5  1691295.7   775813.7
##  [55]   938545.1   382271.0   255419.0   398742.1  1050387.4   276051.9
##  [61]   487427.0   310599.0   340924.0   234698.9   290125.6   382635.7
##  [67]   277363.1   380917.3   265150.4   931568.8   238474.1   398644.6
##  [73]   683109.9  1809786.4  1199178.7   288614.6  1082656.5  1477763.3
##  [79]  2358753.8   330709.1   975141.6  2585246.1  1283257.1   816551.0
##  [85]  2325837.4  2578126.4  1306904.1  2240766.9  1637342.2  1457068.4
##  [91]  1632642.9  1025175.6   885456.9   612403.1   885014.5  1236183.8
##  [97]  1334571.4  1365204.3  4464233.6  3218863.2 17165266.5   762390.6
## [103]   311481.4   310251.5   972807.3  1097472.2  2177944.3   696604.8
## [109]  1269181.3   681341.4  1132474.6  1085186.7   845572.7  1735994.4
## [115]   566402.8   516018.6   729234.7   924512.3   739565.7   804749.8
## [121]  1418617.5  3493791.3  2414014.1  3224540.7   979278.6  1645592.4
## [127]   553237.0  1819413.2   870269.1   924956.5
```

```
# copy BC_withvac_access
BC_withvac_access_vac_area <- BC_withvac_access

# calcuate area outside of the range
BC_withvac_access_vac_area$outside_range_ratio <-
    1 - as.vector(BC_vac_access_area/BC_withvac_access_area)

BC_withvac_access_vac_area
```

```
## Simple feature collection with 130 features and 14 fields
## Geometry type: MULTIPOLYGON
## Dimension:     XY
## Bounding box:  xmin: 424860.5 ymin: 172357 xmax: 440631.8 ymax: 189404.6
## Projected CRS: NAD83(2011) / Maryland
## First 10 features:
##    CensusTract               GEO_ID STATE COUNTY  TRACT NAME  LSAD CENSUSAREA
## 1  24510030100 1400000US24510030100    24    510 030100  301 Tract      0.165
```

```
## 2  24510030200 1400000US24510030200    24    510 030200  302 Tract      0.195
## 3  24510040100 1400000US24510040100    24    510 040100  401 Tract      0.463
## 4  24510040200 1400000US24510040200    24    510 040200  402 Tract      0.169
## 5  24510060200 1400000US24510060200    24    510 060200  602 Tract      0.100
## 6  24510060300 1400000US24510060300    24    510 060300  603 Tract      0.072
## 7  24510060400 1400000US24510060400    24    510 060400  604 Tract      0.166
## 8  24510070200 1400000US24510070200    24    510 070200  702 Tract      0.120
## 9  24510070300 1400000US24510070300    24    510 070300  703 Tract      0.088
## 10 24510070400 1400000US24510070400    24    510 070400  704 Tract      0.126
##            County Urban POP2010 LowIncomeTracts HUNVFlag
## 1  Baltimore City     1    3065               1        1
## 2  Baltimore City     1    2342               1        0
## 3  Baltimore City     1    4006               1        0
## 4  Baltimore City     1     838               1        0
## 5  Baltimore City     1    3265               1        0
## 6  Baltimore City     1    1800               1        0
## 7  Baltimore City     1    1183               1        1
## 8  Baltimore City     1    3782               1        0
## 9  Baltimore City     1    1042               1        0
## 10 Baltimore City     1    1241               1        0
##                          geometry outside_range_ratio
## 1  MULTIPOLYGON (((434910.7 17...         0.003027589
## 2  MULTIPOLYGON (((433985.8 18...         0.000000000
## 3  MULTIPOLYGON (((433926.2 18...         0.000000000
## 4  MULTIPOLYGON (((432439.3 18...         0.000000000
## 5  MULTIPOLYGON (((436345.8 18...         0.993809897
## 6  MULTIPOLYGON (((435592.6 18...         0.635798801
## 7  MULTIPOLYGON (((435161.1 18...         0.020309062
## 8  MULTIPOLYGON (((436406 1810...         0.576034505
## 9  MULTIPOLYGON (((435524.7 18...         0.000000000
## 10 MULTIPOLYGON (((435290.8 18...         0.000000000
```

```
# subset for limited access
BC_limvac_access <- subset(BC_withvac_access_vac_area, outside_range_ratio > 0.33)

BC_limvac_access
```

```
## Simple feature collection with 75 features and 14 fields
## Geometry type: MULTIPOLYGON
## Dimension:     XY
## Bounding box:  xmin: 424876.1 ymin: 172357 xmax: 440631.8 ymax: 189404.6
## Projected CRS: NAD83(2011) / Maryland
## First 10 features:
##    CensusTract               GEO_ID STATE COUNTY  TRACT   NAME  LSAD CENSUSAREA
## 5  24510060200 1400000US24510060200    24    510 060200    602 Tract      0.100
## 6  24510060300 1400000US24510060300    24    510 060300    603 Tract      0.072
## 8  24510070200 1400000US24510070200    24    510 070200    702 Tract      0.120
## 11 24510080101 1400000US24510080101    24    510 080101 801.01 Tract      0.894
```

```
## 13 24510080200 1400000US24510080200    24    510 080200    802 Tract      0.332
## 14 24510080301 1400000US24510080301    24    510 080301 803.01 Tract      0.104
## 15 24510080302 1400000US24510080302    24    510 080302 803.02 Tract      0.170
## 21 24510090100 1400000US24510090100    24    510 090100    901 Tract      0.254
## 22 24510090200 1400000US24510090200    24    510 090200    902 Tract      0.671
## 25 24510090500 1400000US24510090500    24    510 090500    905 Tract      0.286
##            County Urban POP2010 LowIncomeTracts HUNVFlag
## 5  Baltimore City     1    3265               1        0
## 6  Baltimore City     1    1800               1        0
## 8  Baltimore City     1    3782               1        0
## 11 Baltimore City     1    3881               1        1
## 13 Baltimore City     1    1585               1        0
## 14 Baltimore City     1    2084               1        0
## 15 Baltimore City     1    2937               1        1
## 21 Baltimore City     1    4251               1        1
## 22 Baltimore City     1    3243               1        0
## 25 Baltimore City     1    1964               1        1
##                          geometry outside_range_ratio
## 5  MULTIPOLYGON (((436345.8 18...           0.9938099
## 6  MULTIPOLYGON (((435592.6 18...           0.6357988
## 8  MULTIPOLYGON (((436406 1810...           0.5760345
## 11 MULTIPOLYGON (((435823.6 18...           0.9934733
## 13 MULTIPOLYGON (((435460.7 18...           0.7137622
## 14 MULTIPOLYGON (((436130 1816...           0.7216300
## 15 MULTIPOLYGON (((436252.3 18...           0.9127772
## 21 MULTIPOLYGON (((433659.8 18...           0.9192974
## 22 MULTIPOLYGON (((435030.3 18...           0.9367304
## 25 MULTIPOLYGON (((434050.3 18...           0.5247381
```

BC_limvac_access contains all the low-income census tracts with limited access to a vaccination site which as such qualify as vaccination deserts (based on our definition in Section 1.1). To obtain a list or data frame with all possible vaccination deserts we have to add the "no-access" low-income tracts. We can do so with the function **rbind()**, but we need to add an **outside_range_ratio** variable to the **BC_novav_access** data frame. Since the all census tracts in this data frame are outside the range, all entries are set to one.

```
# combine no access with limited acces
BC_novac_access$outside_range_ratio <- 1

BC_VacDeserts <- rbind(BC_novac_access, BC_limvac_access)

BC_VacDeserts
```

```
## Simple feature collection with 106 features and 14 fields
## Geometry type: MULTIPOLYGON
## Dimension:     XY
## Bounding box:  xmin: 424876.1 ymin: 169994.5 xmax: 440631.8 ymax: 189417.3
## Projected CRS: NAD83(2011) / Maryland
```

```
## First 10 features:
##    CensusTract               GEO_ID STATE COUNTY  TRACT    NAME  LSAD
## 1  24510060100 1400000US24510060100    24    510 060100     601 Tract
## 2  24510070100 1400000US24510070100    24    510 070100     701 Tract
## 3  24510090600 1400000US24510090600    24    510 090600     906 Tract
## 4  24510150100 1400000US24510150100    24    510 150100    1501 Tract
## 5  24510150200 1400000US24510150200    24    510 150200    1502 Tract
## 6  24510150300 1400000US24510150300    24    510 150300    1503 Tract
## 7  24510150400 1400000US24510150400    24    510 150400    1504 Tract
## 8  24510150500 1400000US24510150500    24    510 150500    1505 Tract
## 9  24510150600 1400000US24510150600    24    510 150600    1506 Tract
## 10 24510150701 1400000US24510150701    24    510 150701 1507.01 Tract
##    CENSUSAREA         County Urban POP2010 LowIncomeTracts HUNVFlag
## 1       0.092 Baltimore City     1    3222               1        0
## 2       0.112 Baltimore City     1    2957               1        0
## 3       0.154 Baltimore City     1    3402               1        1
## 4       0.143 Baltimore City     1    3211               1        0
## 5       0.162 Baltimore City     1    2699               1        0
## 6       0.154 Baltimore City     1    2478               1        1
## 7       0.315 Baltimore City     1    3724               1        0
## 8       0.367 Baltimore City     1    1543               1        0
## 9       0.370 Baltimore City     1    3412               1        1
## 10      0.331 Baltimore City     1    1696               1        1
##    outside_range_ratio                       geometry
## 1                    1 MULTIPOLYGON (((436868.1 18...
## 2                    1 MULTIPOLYGON (((436868.1 18...
## 3                    1 MULTIPOLYGON (((435043.8 18...
## 4                    1 MULTIPOLYGON (((431016 1817...
## 5                    1 MULTIPOLYGON (((430202.4 18...
## 6                    1 MULTIPOLYGON (((429669 1824...
## 7                    1 MULTIPOLYGON (((429829.8 18...
## 8                    1 MULTIPOLYGON (((428945.2 18...
## 9                    1 MULTIPOLYGON (((428244.4 18...
## 10                   1 MULTIPOLYGON (((428077.1 18...
```

Last, we map the potential vaccination deserts of Baltimore City. To make the map more appealing, we will clip the census tract map to the Baltimore City physical boundaries map.

```
BC_county_boundary <- subset(MD_counties_6487, COUNTY == "Baltimore City")

BC_county_boundary <- st_union(st_buffer(BC_county_boundary, dist = 20))

BC_CensusTracts_phys <- st_intersection(BC_CensusTracts, BC_county_boundary)

BC_LowIncome_phys <- st_intersection(BC_LowIncome, BC_county_boundary)

BC_VacDeserts_phys <- st_intersection(BC_VacDeserts, BC_county_boundary)

map_BC_phys <- tm_shape(BC) +
               tm_fill(col = "lightcyan3") +
```

```
                tm_borders() +
                tm_shape(BC_CensusTracts_phys) +
                tm_fill(col = "antiquewhite") +
                tm_shape(BC_LowIncome_phys) +
                tm_fill(col = "orange") +
                tm_shape(BC_VacDeserts_phys) +
                tm_fill(col = "red") +
                tm_shape(BC_CensusTracts_phys) +
                tm_borders() +
                tm_shape(BC) +
                tm_borders(col = "black",
                           lwd = 1.5) +
                map_vac_BC +
#Legend
                tm_add_legend(type = "symbol",
                    labels =c('Vaccination Site',
                              'Low-income Tract',
                              'Low-income Tract flagged',
                              'as Vaccination Desert'),
                    size = c(0.5, 0.65, 0.65, 0),
                    shape = c(25, 22, 22, 20),
                    col = c('green', 'orange', 'red', 'white'),
                    title = 'Legend') +
                tm_layout(fontfamily = 'Times',
                    legend.position = c(0.025, 0.195),
                    legend.text.size = 0.75,
                    legend.width = 1) +
                tm_scale_bar(position = c("0.015", "0.0015"),
                             text.size = 0.5) + #add (default) scale
                tm_compass(type = "8star", size = 2.5,
                           position = c("0.1125", 0.07)) #add compass

map_BC_phys
```

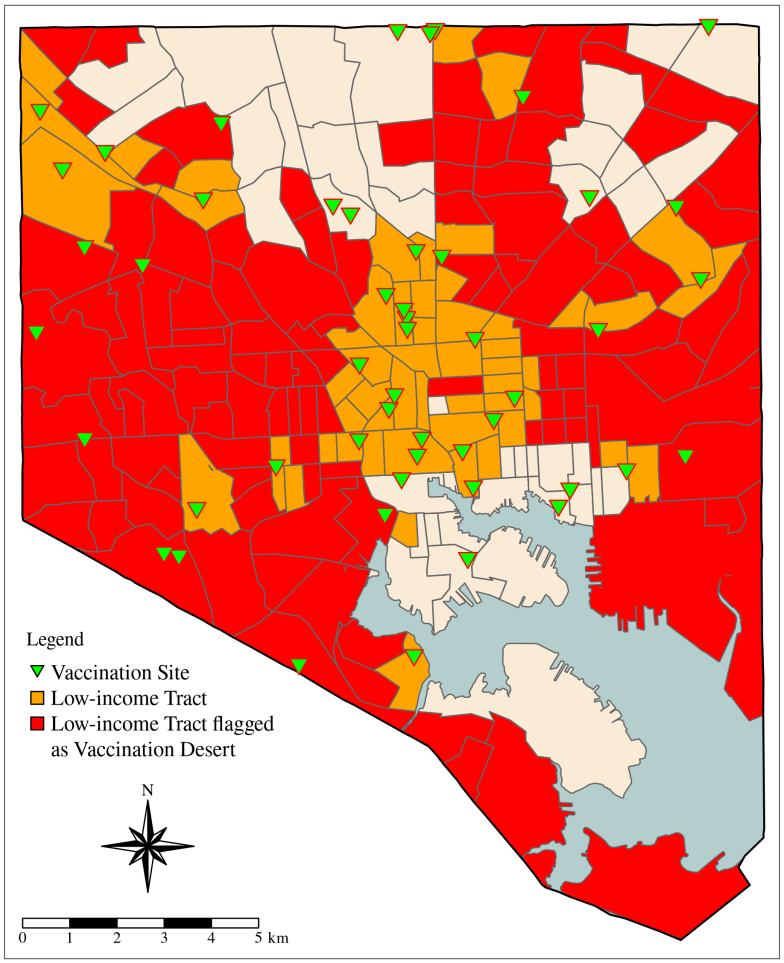

***FIGURE 6.9**. Map of Baltimore City showing low-income census tracts (highlighted in orange) and possible vaccination deserts (highlighted in red).*