Ten Simple Rules for Researchers Who Want to Develop Web Apps

Sheila M. Saia[1], Natalie G. Nelson*[1,2], Sierra N. Young[1], Stanton Parham[1], Micah Vandegrift[3]

[1]Department of Biological and Agricultural Engineering, North Carolina State University, Raleigh, North Carolina, United States of America

[2]Center for Geospatial Analytics, North Carolina State University, Raleigh, North Carolina, United States of America

[3]North Carolina State University Libraries, North Carolina State University, Raleigh, North Carolina, United States of America

*Corresponding Author

Email: nnelson4@ncsu.edu

Keywords:

web applications, web tools, decision support tools, task-centered design

This manuscript was submitted to the PLOS Computational Biology "Ten Simple Rules" collection for peer review on March 18, 2021 and is being prepared for resubmission. This document is a preprint. Supporting information is included at the end of this file.

Introduction

Growing interest in data-driven, decision-support tools across the life sciences (e.g., [1]) and physical sciences (e.g., refs [2,3]) has motivated development of web applications, also known as *web apps*. Web apps can help disseminate research findings and present research outputs in ways that are more accessible and meaningful to the general public--from individuals, to governments, to companies. Specifically, web apps enable exploration of scenario testing and policy analysis (i.e., to answer "what if?") as well as co-evolution of scientific and public knowledge [4,5]. However, the majority of researchers developing web apps receive little formal training or technical guidance on how to develop and evaluate the effectiveness of their web-based decision support tools. Take some of us for example. We (Saia and Nelson) are agricultural and environmental engineers with little experience in web app development, but we are interested in creating web apps to support sustainable aquaculture production in the Southeast. We had user (i.e., shellfish growers) interest, a goal in mind (i.e., develop a new forecast product and decision-support tool for shellfish aquaculturalists), and received funding to support this work. Yet, we experienced several unexpected hurdles from the start of our project that ended up being fairly common hiccups to the seasoned web app developers among us (Young, Parham). As a result, we share the following Ten Simple Rules, which highlight take home messages, including lessons learned and practical tips, of our experience as burgeoning web app developers. We hope researchers interested in developing web apps draw insights from our (in)experience as they set out on their decision support tool development journey.

We focus on web apps, rather than mobile phone applications because advances in web app coding frameworks (e.g., ReactJS, https://reactjs.org/) make it possible to seamlessly scale web apps across multiple devices (e.g., phones, computers, and tablets). *Web apps* are web-based,

interactive, and dynamic tools. By *web-based*, we mean that they are available through the internet, rather than installed and run on a computer (i.e., run locally). By *interactive*, we refer to the ability of users to filter web app information or change web app settings to get the specific information they need. By *dynamic*, we refer to information on the web app that is updated over time (e.g., every few seconds, every day). Many web developers separate web apps into two main components: the frontend and the backend (Figure 1). The *frontend* represents everything the user sees on their device screen while the *backend* represents parts of the web app that only the web developers see (Figure 1b). The backend typically includes: (1) scripts (i.e., computer code) written in a backend language (e.g., Java, Python) to support the frontend appearance and backend functionality of the web app (i.e., how periodic updates are made to the frontend), (2) databases (e.g., MySQL) to store data for the web app and its users, and (3) web services (e.g., Google Cloud Platform, https://cloud.google.com/) to present the updated web app to users and connect the user's frontend experience with the backend tasks via the web app (Figure 1c-e). Most commonly, a trained or experienced web developer will specialize in one particular component; however, some web developers may specialize in the *full stack*, which refers to the frontend and backend of the web app combined.

Throughout this Ten Simple Rules paper, we reflect on our experiences developing the aforementioned decision-support tool and web app, called "ShellCast" (https://go.ncsu.edu/shellcast), as well as how our experience applies more broadly to researchers venturing into web development. ShellCast is a non-commercial product, but researchers interested in commercializing their web apps can look to other articles in the Ten Simple Rules collection [6,7]. Briefly, ShellCast users can sign up to create an account and receive a text

message and/or email notification (Figure 1f) at the start of each day that will alert them of imminent rainfall events over the next 1 to 3 days, the occurrence of which can result in restrictions to their shellfish harvesting operations. By creating an account with the web app, users select a geographic location or locations that they would like to receive notifications for and their preferred notification type (i.e., text message, email, or both). Users can also view their notifications and notification locations on the web app main page (Figure 1b). There are many backend aspects to ShellCast that users do not see (Figure 1c-e). These include but are not limited to: (1) timed running of web app backend tasks and code, also known as *cron jobs,* that update the web app database(s) each day at 7am and (2) timed interactions between the web app database(s) and third-party notification providers (i.e., email and text message notification services).

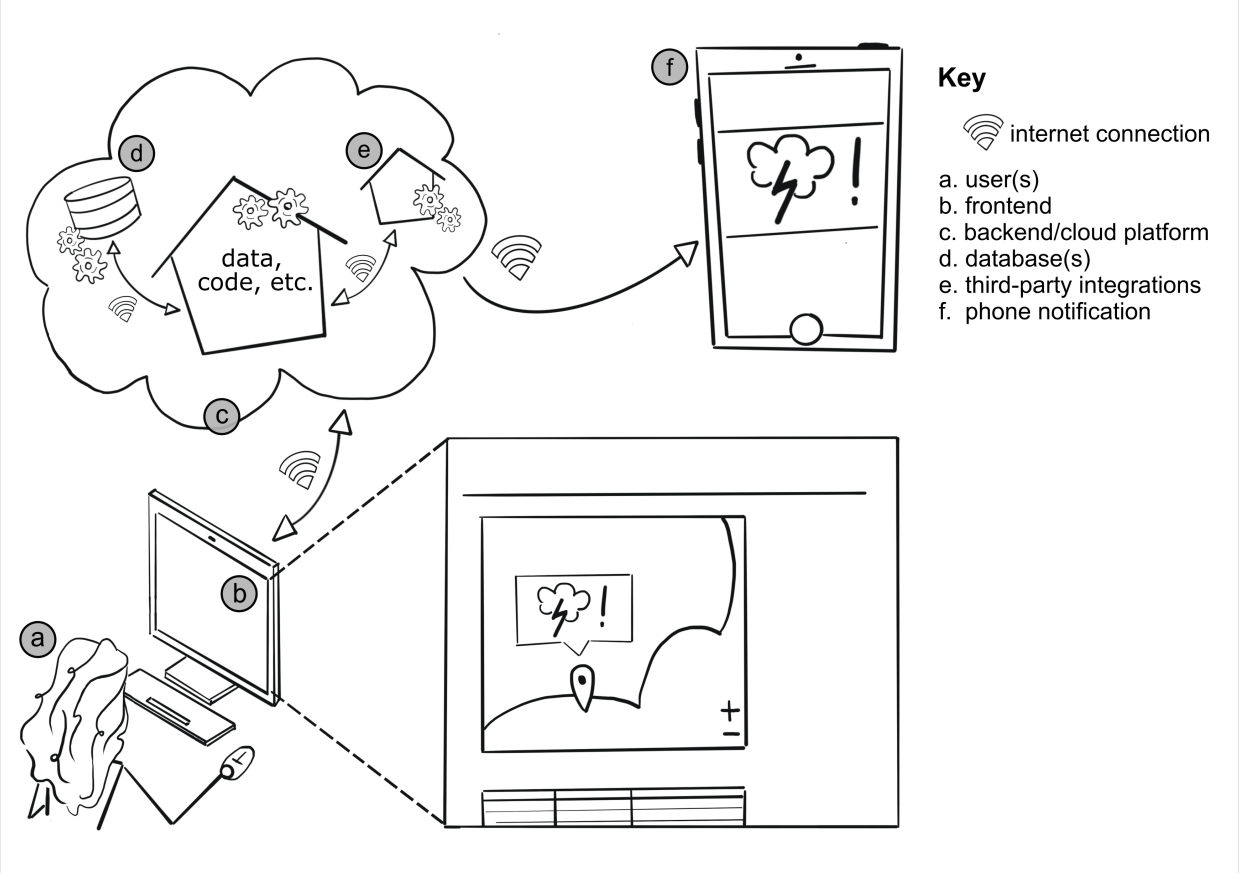

Figure 1. Major components of a web application (web app). In this line drawing, the (a) user is shown interacting with the (b) frontend of the web app. The frontend is updated based on changes that occur in the backend (c and d). Updates that occur in the backend can also trigger other actions, such as (f) text or email notifications via (e) third-party integrations. Image Credit: Sheila M. Saia (CCBY 4.0).

Rule 1: Start with task-centered design

An idea for a web application, no matter how useful and wonderful it may seem, will not be of much use if you cannot articulate *exactly* who is going to use your web app and what *exactly* they will do with it. It is also important to know how folks will use your web app and how they will go about making decisions [8]. Designing a web app around what the user wants is known as

user-centered design. *Task-centered design* is a subset of user-centered design that focuses on specific steps taken by the user, and how the web developer implements these tasks behind the scenes, to achieve the needs of the web app user. Task-centered design is widely studied and used for web app development [9,10]. See reference [9] for a thoughtful introduction to implementing task-centered design. Additionally, they emphasize that it is critical to consider users and their tasks early on in the design process, before jumping directly into web app development. The first step in task-centered design is to conduct a task and user analysis [9]. During this step, it is helpful to find real, potential users and discuss how your proposed web app will integrate with their existing workflow and operations. In addition to collecting their feedback, it is important to collect data about potential users. This may include asking for information such as their education levels, computer and web experience, work environment, domain experience, and motivation. If you have trouble finding potential users, this is a good indication that you may need to rethink your web app concept.

After identifying users and getting feedback, the next step in task-centered design is to develop concrete, detailed examples of tasks users will perform using your web app [9]. Tasks should be (1) representative and describe what the user should do, rather than how they do it, and (2) design independent. Also, tasks should be complete and might include multiple sub-tasks, termed *transition tasks*. For example, a complete ShellCast task would be: “Create a ShellCast account and sign up to get alerts for your geographic shellfish growing area”. An incomplete ShellCast task would be: “Select your shellfish growing area on the map”. At this stage, it is useful to implement an iterative design process using very simplistic *mockups*, also called sketches, illustrations, or wireframes (Figure S1), of the web app and discuss the mockup designs early on

with users and web developers on your team. It is unlikely you will get the web app design right the first time. Getting feedback on low-stakes mockups early in the design process will save you time, money, and resources (see Rule 2). Admittedly, we (Saia and Nelson) did not include mockups in the first version of the ShellCast contract draft (Text S1 and see Rule 5) and were later advised by (very patient) Office of Information Technologies staff at our institution that it was imperative for users and web developers to see mockups prior to the creation of the web app. To illustrate how contracts and mockups are drafted in practice, we offer the final version of the ShellCast contract complete with mockups (Text S2, Figure S1). Developing the mockups was a very useful exercise and helped us work through the details of complete tasks that users would take when using ShellCast. It is important to note that this iterative task-centered design is different from user evaluation, the latter of which is a testing procedure of a more polished web app prototype (see Rule 2).

Rule 2: Remember: Users know best

User testing and evaluation should ideally be conducted throughout the web app development process and include a diverse range of potential users. User testing is important because it allows the web development team (including researchers, like us) to iterate on the web app design and ensure it meets user expectations by the time web development is complete. There are commercially available services and companies dedicated to conducting user tests; however, if budget constraints prevent you from using these services, you can conduct your own user testing with a little guidance (e.g., [9]). In general, there are three main types of user testing: (1) formative evaluations, which are performed during iterative design to find web app usability issues to be fixed during the next iteration; (2) field studies, which find problems in web app use

contexts and collect qualitative observations; and (3) controlled experiments, which test hypotheses and collect quantitative observations about web app use [9,11]. User testing can be done remotely and in-person. In general, user testing requires finding actual users, selecting tasks for evaluation, providing users with a prototype web app for use, deciding what data to collect, choosing an evaluation method, and collecting data. There are many types of evaluation methods, each with their own purpose, pros, and cons. A full survey of evaluation methods is outside the scope of this paper, but a few common methods are listed below for consideration.

Surveys are one of the most common user testing methods and can provide valuable information about your users, how they think, and what they want from the web app. Surveys are most useful when collecting data from a large number of people; however, one drawback of surveys is that they provide broad and shallow feedback. When more in-depth information is needed, methods such as case studies, interviews, and focus groups with smaller groups of people are more appropriate. Paper prototyping is a low-stakes method to test web apps early on where users can move around pieces of paper, each depicting rough drawings of different views of a web app, to explore how they would perform various web app tasks [12]. Case studies take an in-depth look at a specific instance within a real-world context and usually collect qualitative data that help explain user behavior (chapter 7 of [11]). Direct discussions with individual users (*interviews*) and groups (*focus groups*) of users can also provide useful data and perspectives that shallow surveys might miss. User testing discussions can be structured using a rigid script to present questions in a well-defined and consistent manner. Discussions can also be semi-structured or unstructured to allow room for more exploration in discussions (chapter 8 of [11]). Finally, when more final prototypes are available, a variety of testing apps and services exist online for use at a

range of price points. A few examples include User Testing (https://www.usertesting.com/) or UsabilityHub (https://usabilityhub.com/).

We (Saia and Nelson) knew very little about user testing when developing ShellCast. Despite our limited knowledge, we understood that feedback was important and implemented two user testing periods using surveys administered via Google forms. The goal of these surveys was to learn about potential issues that users might encounter when interacting with an initial version (user test #1, Text S3) and improved version (user test #2, Text S4) of ShellCast. While participants in these tests were not actual users of the web application (i.e., shellfish growers), they were colleagues in our field who have connections with actual users. We are in the process of rolling out ShellCast to actual users and conducting additional user testing through surveys and focus group discussions. Our focus group discussions will be led by a professional facilitator. We chose not to involve actual users in the very early stages of ShellCast's development out of respect for their time and to build trust; we wanted to make sure the basic functionality was established and ShellCast was safe, from a privacy standpoint, to use. Plus, our potential user base is relatively small (i.e., ~350 active shellfish leases in NC as of 2020, [13]), so we do not have a large pool of testers to recruit from. The two ShellCast user testing surveys we distributed early in the app development process proved very helpful in uncovering issues associated with signing up for an account, getting text notifications, and deciding which and how much information to convey to web app users.

Rule 3: Make it accessible

To ensure web apps can be used by all, it is important that researchers adhere to accessibility guidelines. Here, we consider accessibility not as a measure of openness as described by Findable, Accessible, Interoperable and Reusable (FAIR) [14,15] research output guidelines, but rather as a measure of a web app's utility to people of diverse abilities. Website accessibility is important because it helps ensure a broad group of people will be able to use your app and also because there are laws mandating that your applications and websites are accessible. Being based in the United States (US), we focus on US laws and standards in this Ten Simple Rules paper. US-specific accessibility laws that impact researchers developing web apps include: Title 2 [16] and Title 3 [17] of the Americans with Disabilities Act, associated web accessibility standards such as Section 504 through the United States Department of Education Office of Civil Rights [18], and Revised Section 508 and 255 Guidelines of the Rehabilitation Act [19]. For researchers in the US, these legal standards are enforced by the US Department of Education's Office of Civil Rights. These standards incorporate Web Content Accessibility Guidelines [20] developed by the international World Wide Web Consortium Web Accessibility Initiative. If these laws and standards are not met, accessibility conformance can be enforced by informal complaints made directly to the web developer or formal complaints made through the Office of Civil Rights or through lawsuit to the university.

You should plan for accessibility as early as possible in the web app development process. This includes taking time early on to ensure your web app is designed so it can be accessed by assistive technologies such as dictation software, screen readers, refreshable Braille displays, and many others. For example, information provided in a map can also be made available in a table format (Figure 1b zoomed inset), the latter of which is more accessible to screen readers. You

can also practice accessibility when developing surveys and feedback forms [21], captioning web app-related videos, and including alt-text along with all images. *Alt-text* is text that describes an image (non-textual) and is assigned as an image attribute in the frontend HTML tag for the image (e.g., `<img src="picture.png" alt="A picture">` ; in the web app backend language [22]. Assistive technologies like screen readers rely on the image attribute to communicate meaning to their users. Some of the most common web accessibility issues (e.g., low color contrast, unlabeled form fields, no alt-text or video captions) are fairly easy for web developers to fix [23].

Digital accessibility standards are fairly new and can be confusing, especially if you have little or no experience navigating them. Therefore, second to planning ahead, researchers can ask web accessibility coordinators for help reviewing and addressing potential web app accessibility issues (see Rule 7). The organizational structure of web accessibility coordinators at each institution is unique; however, these staff are often based in a researcher's office of information technology, office of diversity and inclusion, office of disability resources, office of communications, or office of digital accessibility. Last but not least, web app developers can use web accessibility evaluation tools to scan their web app for accessibility issues and implement solutions to these issues via updates to frontend design and backend scripts. Two example web accessibility evaluation tools include the pope.tech platform (https://pope.tech/) and the ANDI bookmarklet (https://github.com/SSAgov/ANDI). For example, during the development of ShellCast, we scanned the application with pope.tech and discovered the contrast of our colors needed to be increased, which we likely would have never realized had we not used the pope.tech tool.

Rule 4: Protect your users

Researchers developing web apps have a responsibility to (1) protect information that users share and (2) be transparent about how data collected through the web app will be used. If based in the European Union, you must adhere to strict data privacy laws laid out in the European Union's General Data Protection Regulation (GDPR, [24,25]). However, we recommend non-European-based researchers (like us) do their best to meet GDPR requirements because they protect the user and ensure the web app is globally inclusive. Depending on the scope of your web app, researchers in the United States may look to notable privacy protection laws including: Health Insurance Portability and Accountability Act, Family Educational Rights and Privacy Act, Children Online Privacy Protection Act, and California Consumer Privacy Act. Web app security and privacy is especially important if users sign up, log in, and receive a service because information collected during this process may include personal identifiers like email addresses, phone numbers, mailing addresses, and other personal information. In our case, users can log into ShellCast, set up a profile, add map pins, and select text message and/or email notification preferences.

To put security and privacy protections into practice, the easiest approach is to leverage third-party integrations including sign up/sign in using Gmail, Facebook, Microsoft, Twitter, etc. because these services will manage passwords for you. Additionally, you can use cloud-based web services to offload typical security maintenance; therefore, ensuring your web app is deployed with the latest web security updates. In our case, our institution has access to Gmail and Google Cloud Platform, so ShellCast is built with these services. It is also important to have

a Secure Sockets Layer to encrypt user inputs and keep them safe from hackers. Additionally, you can include a privacy policy on your website that includes details on how information will be protected and used by the researchers. Privacy statement starter templates can be found online (e.g., [26]). As an example, you can view the ShellCast Privacy policy (Text S5). While it may take some planning ahead, you may also consider giving users the ability to delete their account and download their data; this is included in the GDPR discussed above. Last, if you expect to publish user feedback in peer-reviewed publications, you must get Institutional Review Board approval from your institution before doing so.

Rule 5: Hire a web developer

Researchers interested in creating web apps can contract out for web development. Doing so will improve web app functionality and professional appearance since the firm will put together a team of specialists to work on your web app. Typically, this team will include: a project manager, backend developer, frontend developer, and possibly a graphic designer and documentation writer. If you are interested in contracting a web development firm, your first step will be to develop a request for proposals (RFP) that will then be posted and advertised by your institution. Web development firms will then submit any follow up or clarifying questions, which you will need to answer so your institution can post your responses along with the public RFP. After reading your responses, web development firms will then submit proposals (including their budget) to your institution for your consideration. You will then choose which firm to contract with based on these proposals. Importantly, take time to think through web app tasks before writing and publishing the RFP. The RFP must be extremely precise and specific; it should outline all expectations for the web app, including its appearance and functionality (see Rule 1).

If functions or features of the web app need to be adjusted at a later point, a contract renegotiation may be necessary. Consequently, web app expenses and development time are likely to mount if changes are needed. From our experience, if you are inexperienced in web app development, you may struggle to prepare an accurate and fully specified RFP, which can create a risky situation since you may go into contract for work that is not reflective of what you seek to accomplish. In addition to the challenges that come with preparing a precise RFP, budgets associated with web development firm projects can be large, particularly since they work in teams of specialists.

We originally planned to contract with a web development firm for ShellCast, posted an RFP through our institution's advertising portal, and received several requests from potential web development firms asking for additional web app details. We reached out to experts in our institution's Office of Information Technologies for help answering these questions, and with their support, we revised the RFP. See the supplemental material for the early (Text S1) and final (Text S2) versions of our RFP. Despite only having budgeted $20,000 USD for all web app-related expenses, we received proposed project budgets ranging from $60,000 to $180,000 USD. The more specificity you provide in the RFP, the smaller the proposed project budget ranges will be. Confronted with these outsized proposed budgets relative to our available funds, we explored alternatives. It is possible that a professional freelance full-stack developer may have been able to create our application at budget-friendly rates, but we struggled to connect with freelancers through our institution's traditional advertising portals. After going through this process, we learned that we could ask our institution to post the RFP on our local small business association listserv, small business and technology development center listserv (e.g.,

https://sbtdc.org/offices/ncsu/), and on popular freelance job websites such as Fiverr (https://www.fiverr.com/) or Upwork (https://www.upwork.com/), among others. The second alternative we identified was to hire a computer science student, which is the option we ultimately went with for ShellCast.

Although still in training, many undergraduate and graduate computer science students have the skills needed to develop web apps—plus, they are eager to gain practical experience. We were able to hire the student (Parham) on an hourly basis, which provided flexibility as we ventured into new territory and identified additional features and functions during the development process that we had not originally considered (because we are novice web developers). Had we contracted with a web development firm, we likely would have been limited in our ability to incorporate these new ideas generated by the web app development process into ShellCast without contract renegotiation. By hiring a student, we also avoided many of the administrative tasks and overhead costs associated with hiring an external freelance web developer or web development firm. Most importantly, we found that student applicants to the ShellCast team were eager to try out new tools that would best serve the project (instead of using tools they felt most comfortable with) and work with us despite our lesser experience. However, hiring a student to develop your app can come with sustainability challenges (see Rule 10). Therefore, we argue there is a need for institutions and research sponsors to provide more resources that support expert software development.

Rule 6: Expect expenses

To the unseasoned web application developer, the costs associated with maintaining an application can be surprising (e.g., see our web app budget underestimation story in Rule 5). At a minimum, plan to budget for a web developer, web hosting fees, Secure Sockets Layer certificate for web app encryption, domain name costs, and cloud computing services. Setting aside a "rainy day" or "emergency" fund is also wise, as unexpected issues can arise that may derail the development or use of your app.

Web hosting refers to a suite of services needed to make a webpage available to users. When a webpage is constructed, it is stored or "hosted" on an internet server (Figure 1c). For example, ShellCast uses Google Cloud Platform to accomplish storage and hosting. Users accessing a web app enter the web address (i.e., URL) in their web browser (Figure 1b) and the web browser connects to the internet service (e.g., Google Cloud Platform) hosting the web app. You can think of web hosting fees as rent paid for the space your web app occupies on an internet server. Similar to rent, web hosting fees are paid over periods (i.e., annually, monthly), and depend on whether the web app is static or dynamic, how much storage space you need (e.g., 10 GB), the number of people you expect to use the web app at the same time (i.e., network traffic), and in the case of dynamic web apps, the additional computing resources required. Many web hosting providers also offer domain name purchasing (e.g., GoDaddy, Dream Host, Google Domains). Domain names can be purchased from a domain registrar (e.g., GoDaddy, Dream Host, Google Domains) on a recurring basis. Notably, many institutions, such as universities, provide internal web hosting and domain name services at low rates, so be sure to check with experts at your institution before spending your hard-earned grant money.

To create a static webpage, only web hosting and domain name purchasing is needed. However, some web apps may require *cloud computing* (Figure 1c), which refers to the storing and processing of information and data over the internet. Common cloud computing providers include Google Cloud Platform, Amazon Web Services, Microsoft Azure Cloud. Additionally, if you plan to send emails or text messages as one of the functions of your application, expect to pay for each and every message sent using third-party integrations for emails (e.g., Mailchimp, SendGrid, MailGun) and Short Message Service (SMS) texts (e.g., Twilio, Nexmo). Although the rates per message can be very low, these costs grow quickly as you scale up your web app. For ShellCast, we used Amazon Web Services Simple Email Service.

Lastly, we recommend you consider including funds to support user testing (see Rule 2), such as for contracted services or reimbursement for the testers' time. For ShellCast, we budgeted for a professional facilitator to lead focus group discussions with shellfish growers who pilot the use of our web app, but we would have also benefited from having budgeted for participant support costs and professional user testing services.

Rule 7: Leverage institutional expertise

When starting on your web development journey, look to professionals at your institution for feedback and support; these staff may share helpful resources and be great sounding boards throughout web app development. These professionals include information technology staff, library staff, computer scientists, user-experience/user-design staff, graphic designers, web accessibility staff (see Rule 3), and many more. You may also benefit from including students

371 from computer science or other related fields on your team (see Rule 5). These students are often
372 looking for hands-on experience as they work toward the completion of their degree.
373
374 We found several professionals in the information technologies office, library, and
375 communications office that supported our work on ShellCast. Specifically, our university has
376 designated outreach technologies staff within the information technology office; these staff
377 regularly meet with researchers and give them feedback on resources, tools, and services that are
378 available to support university-related web app development. In a series of meetings with (the
379 very patient) outreach technologies staff, we were introduced to mockups (see Rule 1), university
380 supported web app structures (see the Introduction, Figures 1c-e), database structures, web
381 accessibility standards (see Rule 3), user privacy protection (see Rule 4), skills needed by the
382 web developer to bring our app to fruition, user testing (see Rule 2), and much more. In addition
383 to getting feedback from outreach technologies staff, we also contacted library staff to review the
384 ShellCast web app documentation (see Rule 10). This was especially helpful because the
385 university has staff (Vandegrift) who specialize in documentation, licensing, and sustainability of
386 open source software. Our funders required ShellCast to be open source, although we intended to
387 pursue open source standards all along. Additionally, we leveraged the expertise of a graphic
388 designer in the communications office to help us develop the ShellCast mark as well as an
389 infographic. These graphics enhanced the appearance of ShellCast and helped us explain how
390 ShellCast works to members of the general public. In the end, working with a computer science
391 student and in-house graphic designer kept us well within our budget.
392

Rule 8: Track your progress with existing collaboration tools

There are a number of existing resources and tools to help researchers and web developers keep track of their work, plan out project milestones, and pursue open science. Reproducible and open work is often highly recommended by professional societies (e.g., [27]) and a requirement of federal funding; therefore, it's important that researchers are aware of the expectations of their sponsors (e.g., [28]). Open and reproducible work may also be required by publishers (e.g., American Geophysical Union journals [29], Public Library of Science (PLOS) journals [30]), should researchers wish to eventually publish a paper on their web app. To keep track of changes to web app code while working with others, you can use version control software [31–33]. You can also use Kanban project management tools [34] such as those provided through platforms like GitHub projects (https://github.com/features/project-management/), Trello (https://trello.com/), Teamwork (https://www.teamwork.com/), Jira (https://www.atlassian.com/software/jira), and many others. Project management tools can help the web app team chart project milestones, create and assign tasks, and keep track of emerging issues (Figure S2).

While building the ShellCast web app, we used both Git and GitHub to collaborate on and keep track of code (Figure S2). We created a GitHub project within the ShellCast web app repository and used this to track each team member's progress on different tasks (also referred to as "issues" in the GitHub platform) as they moved from the "To Do" pile, to the "In Progress" pile, to the "Done" pile. We could comment on tasks in GitHub, which was helpful when referring back to past conversations and justifications for decisions even after tasks were completed. We could also use the issues to take notes and save helpful resources that we did not want to lose or could be important for new team members joining in the future.

Rule 9: Estimate task times, then double them

We recommend generously estimating the time needed to develop a web application, especially if you are new to application development. Keep in mind that even small changes to a web app can lead to reconfigurations of database structures and backend web application logic, often resulting in seemingly minor changes requiring a considerable amount of time to complete. Researchers should not be surprised if tasks will change or be carried out differently after user testing. Make sure you budget conservatively for time needed to revise the application after receiving feedback from user testing (see Rule 2) and to document the web app (see Rule 10). Furthermore, we acknowledge that estimating task times can be very difficult because they depend on a number of things including: (1) the number of developers working on the web app, (2) the experience the developers have working with the technologies that your web app needs, (3) the size and complexity of the web app, (4) the specificity of the web app functionality (i.e., whether or not you know exactly what the web app will do, how it will look, and how it will behave), (5) project organization and efficiency, and many other uncertainties which are tough to all list here.

In our experience, initial development of ShellCast took our web developer (Parham) approximately 275 hours, with revisions following two rounds of user testing amounted to 75 hours. This time does not include time spent by our second web developer (Saia) to develop the ShellCast algorithm and get up to speed on connecting to and updating the ShellCast database. To provide some more context, ShellCast is a small web app that has fairly simple functionality and had two developers. One developer (Parham) worked on the web app, database,

notifications, hosting, and documentation while the other developer (Saia) worked on the forecast calculations, database, and documentation. Additionally, ShellCast requirements were specific and clearly set in the beginning of the project; however, we had to make some significant changes along the way after having more in-depth conversations with collaborators; these changes were separate from those we made based on user testing feedback.

Rule 10: Make it last: Plan for the long haul

Maintenance is a core tenet of effective web app management. Without proper maintenance and support (i.e., funding), the impact of your web app will be cut short. Web apps are commonly included in grants as a mechanism for disseminating research findings to stakeholders, yet, in our experience, proposals rarely include plans on how a proposed web app will exist beyond the duration of the one- to three-year grant. Plus, the web app development phase may occur towards the end of a project period, which leaves little time for the web app to be discovered and used. Therefore, to ensure utility and longevity of your web app, determine who will be designated as the web app maintainer(s) [32,35]. Additionally, we recommend budgeting time (and funds) to documenting your web app as well as incorporating documentation and project sustaining best practices (e.g., [36–38]). If your code relies on established R packages, Python libraries, or other software with particular version numbers, consider using tools like Docker (e.g., [39]) or Conda (e.g., https://docs.conda.io/en/latest/) to manage web app *dependencies*—the software and code versions that your web app depends on to run—and make it easier for others to replicate your web app. For ShellCast, we explicitly included documentation of typical developer tasks in a DEVELOPER.md markdown file and included several other markdown files to document other important web app-related setup steps and tasks. If researchers are interested in learning more

about doing open and reproducible science, there are many resources available (e.g., [40,41]), several of which are in the Ten Simple Rules collection [15,31,42,7,43,35,44–46].

It may also help to make a plan and initiate involvement of the user community (see Rule 2), including researchers in related fields who are interested in maintaining the web app into the future. This group of interested users is often referred to as a *maintainer community*. Look to collaboration guidelines such as those proposed by Mozilla Open Leaders Open Project for maintainer community best practices [47] or the Sustain online discussion board for open source projects (https://discourse.sustainoss.org/). Last but not least, we reiterate the importance of leveraging technology services offered through your university (e.g., domain names, see Rule 7), to limit issues that could arise if your maintenance funds are or will become limited.

In many cases, app discoverability and longevity are linked and can be improved by using established cyberinfrastructure and building upon existing web apps. Dr. Julia Stewart Lowndes, Director of Openscapes (https://openscapes.org), encourages researchers interested in open and reproducible science (including software and web app development) to ask themselves: "[Am] I being as open as I can be, am I being as inclusive as I can be, and will I be able to maintain what I'm starting?" [32,48]. Before beginning web app development, scan the web app landscape to see if there are similar open source projects that could be adapted, rather than building a web app from scratch. Your subject specialist librarian are a great resource for starting this scan (see Rule 7) and can also help you navigate evolving practices in software citation (e.g., [49]), data publishing (e.g., [50]), and other emerging topics that are web app-related. *Research infrastructure*—the services, protocols, standards, and software that the academic ecosystem

needs to perform its functions—is constantly modernizing and standardizing. Thus, there are opportunities to build sustainable products (i.e., your web app) that are also interoperable across the landscape.

Since routine web app operation requires a domain name, web hosting, and cloud computing services, funds are needed for long-term support (see Rule 6). Researchers interested in developing web apps should acknowledge the need for continued support in proposals and outline potential funding sources that they can pursue to support web app longevity. Acknowledging that web apps require regular maintenance and enduring financial support demonstrates understanding of the realistic resources it takes for a web app to come to fruition; thus, increasing the researcher's credibility. Applying for alternate funding opportunities like Fund Open Source Software (https://fundoss.org/) can stretch the longevity of your web app.

Conclusions

Web apps serve as powerful tools to extend research findings to members of the public, but their development is not easy. Successfully creating web apps for educational and outreach purposes requires careful and thoughtful planning to ensure the web apps are relevant to end users, accessible to all, and long-lasting. Here, we outline Ten Simple Rules for researchers to consider as they venture out on their own web app development journeys, with several of these rules serving as "lessons learned" from our own personal experiences developing the web app, ShellCast. In summary, a good thought to keep in mind is: "Build for usability, budget in flexibility, and begin maintenance plans from the start."

Acknowledgements

Special thanks to Everette Allen, Walter Turner, and Crystal Tenan their critical feedback on this manuscript and for teaching us many of the lessons summarized here. This work was supported in part by the North Carolina Sea Grant (R/20-SFA-4), United States Department of Agriculture (USDA) Food and Agriculture Cyberinformatics Tools (FACT) project (2019-67021-29936), and USDA National Institute of Food and Agriculture (NIFA) Hatch projects 1021499 and 1016068.

Author Contributions

SMS, NGN, SNY were involved in conceptualization of this manuscript and SMS, NGN, SNY, SP, and MV wrote the manuscript draft. NGN acquired funding for ShellCast, administered the ShellCast project, and supervised SMS and SP. SMS created the visualizations used in the manuscript and supporting documentation. All authors provided critical feedback by reviewing and editing the manuscript.

References

1. Bilimoria KY, Liu Y, Paruch JL, Zhou L, Kmiecik TE, Ko CY, et al. Development and Evaluation of the Universal ACS NSQIP Surgical Risk Calculator: A Decision Aid and Informed Consent Tool for Patients and Surgeons. Journal of the American College of Surgeons. 2013;217: 833–842. doi:10.1016/j.jamcollsurg.2013.07.385

2. Cooke T, Lingard H, Blismas N, Stranieri A. ToolSHeD ™: The development and evaluation of a decision support tool for health and safety in construction design. Engineering, Construction and Architectural Management. 2008;15: 336–351. doi:10.1108/09699980810886847

3. Horita FEA, Albuquerque JP de, Degrossi LC, Mendiondo EM, Ueyama J. Development of a spatial decision support system for flood risk management in Brazil that combines volunteered geographic information with wireless sensor networks. Computers & Geosciences. 2015;80: 84–94. doi:10.1016/j.cageo.2015.04.001

4. Graffy EA, Booth NL. Linking environmental risk assessment and communication: an experiment in co-evolving scientific and social knowledge. International Journal of Global Environmental Issues. 2008;8: 132–146. doi:10.1504/IJGENVI.2008.017264

5. Booth NL, Everman EJ, Kuo I-L, Sprague L, Murphy L. A Web-Based Decision Support System for Assessing Regional Water-Quality Conditions and Management Actions1: A Web-Based Decision Support System for Assessing Regional Water-Quality Conditions and Management Actions. Journal of the American Water Resources Association. 2011;47: 1136–1150. doi:10.1111/j.1752-1688.2011.00573.x

6. Fletcher AC, Bourne PE. Ten Simple Rules To Commercialize Scientific Research. PLOS Computational Biology. 2012;8: e1002712. doi:10.1371/journal.pcbi.1002712

7. Masum H, Rao A, Good BM, Todd MH, Edwards AM, Chan L, et al. Ten Simple Rules for Cultivating Open Science and Collaborative R&D. PLOS Computational Biology. 2013;9: e1003244. doi:10.1371/journal.pcbi.1003244

8. Grêt-Regamey A, Sirén E, Brunner SH, Weibel B. Review of decision support tools to operationalize the ecosystem services concept. Ecosystem Services. 2017;26: 306–315. doi:10.1016/j.ecoser.2016.10.012

9. Lewis C, Rieman J. Task-Centered User Interface Design: A Practical Introduction. Boulder, Colorado; 1993. Available: http://hcibib.org/tcuid/tcuid.pdf

10. Ruiz J, Serral E, Snoeck M. Unifying Functional User Interface Design Principles. International Journal of Human–Computer Interaction. 2021;37: 47–67. doi:10.1080/10447318.2020.1805876

11. Lazar J, Feng JH, Hochheiser H, editors. Research Methods in Human Computer Interaction. Morgan Kaufmann; 2010.

12. Snyder C. Paper Prototyping: The Fast and Easy Way to Design and Refine User Interfaces. San Francisco, CA: Elsevier; 2004.

13. North Carolina Division of Marine Fisheries (NCDMF). N.C. Shellfish Lease and Aquaculture Permitting Program. In: North Carolina Department of Environmental Quality [Internet]. 2020 [cited 11 Mar 2021]. Available: http://portal.ncdenr.org/web/mf/habitat/enhancement/shellfish-leases

14. Wilkinson MD, Dumontier M, Aalbersberg IjJ, Appleton G, Axton M, Baak A, et al. The FAIR Guiding Principles for scientific data management and stewardship. Scientific Data. 2016;3: 160018. doi:10.1038/sdata.2016.18

15. Garcia L, Batut B, Burke ML, Kuzak M, Psomopoulos F, Arcila R, et al. Ten simple rules for making training materials FAIR. Markel S, editor. PLOS Computational Biology. 2020;16: e1007854. doi:10.1371/journal.pcbi.1007854

16. United States Department of Justice Civil Rights Division. State and Local Governments (Title II). In: Information and Technical Assistance on the Americans with Disabilities Act [Internet]. 2011 [cited 11 Mar 2021]. Available: https://www.ada.gov/ada_title_II.htm

17. United States Department of Justice Civil Rights Division. Public Accommodations and Commercial Facilities (Title III). In: Information and Technical Assistance on the Americans with Disabilities Act [Internet]. 2011 [cited 11 Mar 2021]. Available: https://www.ada.gov/ada_title_III.htm

18. United States Department of Education Office of Civil Rights. Regulation implementing Section 504 of the Rehabilitation Act of 1973, Title 34 Part 104. US Department of Education (ED); 1973 [cited 11 Mar 2021]. Available: https://www2.ed.gov/policy/rights/reg/ocr/edlite-34cfr104.html

19. United States Access Board. About the ICT Accessibility 508 Standards and 255 Guidelines. In: U.S. Access Board - Revised 508 Standards and 255 Guidelines [Internet]. 2017 [cited 11 Mar 2021]. Available: https://www.access-board.gov/ict/

20. Web Accessibility Initiative (WAI). A customizable quick reference to Web Content Accessibility Guidelines (WCAG) 2 requirements (success criteria) and techniques. In: How to Meet WCAG (Quickref Reference) [Internet]. 2019 [cited 11 Mar 2021]. Available: https://www.w3.org/WAI/WCAG21/quickref/?versions=2.0

21. Web Accessibility Initiative (WAI). Forms Concepts. In: Web Accessibility Tutorials: Guidance on how to create websites that meet WCAG [Internet]. 2019 [cited 11 Mar 2021]. Available: https://www.w3.org/WAI/tutorials/forms/

22. WebAIM. Alternative Text. In: WebAIM: Web Accessibility in Mind [Internet]. 2019 [cited 11 Mar 2021]. Available: https://webaim.org/techniques/alttext/

23. WebAIM. The WebAIM Million - An annual accessibility analysis of the top 1,000,000 home pages. In: WebAIM: Web Accessibility in Mind [Internet]. 2020 [cited 11 Mar 2021]. Available: https://webaim.org/projects/million/

24. European Union. General Data Protection Regulation (GDPR). In: General Data Protection Regulation (GDPR) [Internet]. 2018 [cited 11 Mar 2021]. Available: https://gdpr-info.eu/

25. McCoy O. A legislative comparison: US vs. EU on data privacy. In: European Interactive Digital Advertising Alliance (EDAA) [Internet]. 31 Mar 2020 [cited 11 Mar 2021]. Available: https://edaa.eu/a-legislative-comparison-us-vs-eu-on-data-privacy/

26. Termly Legal Team. Privacy Policy Template. In: Termly [Internet]. 2020 [cited 11 Mar 2021]. Available: https://termly.io/resources/templates/privacy-policy-template/

27. Wizemann T, Ncha S, Gee AW, Shore C, editors. Enhancing Scientific Reproducibility in Biomedical Research Through Transparent Reporting: Proceedings of a Workshop. Washington, DC: The National Academies Press; 2020. doi:10.17226/25627

606 28. Chief Information Officers (CIO) Council. Open Data Policy - Managing Information as an
607 Asset. In: Project Open Data [Internet]. 2019 [cited 12 Mar 2021]. Available:
608 https://github.com/project-open-data/project-open-data.github.io

609 29. American Geophysical Union (AGU). Data Policy. In: AGU Policy: Data [Internet]. 2016
610 [cited 12 Mar 2021]. Available: https://www.agu.org/Publish-with-AGU/Publish/Author-
611 Resources/Policies/Data-policy

612 30. Public Library of Science (PLOS) ONE. Data Availability. In: Public Library of Science
613 (PLOS) ONE [Internet]. 2020 [cited 12 Mar 2021]. Available:
614 https://journals.plos.org/plosone/s/data-availability

615 31. Perez-Riverol Y, Gatto L, Wang R, Sachsenberg T, Uszkoreit J, Leprevost F da V, et al.
616 Ten Simple Rules for Taking Advantage of Git and GitHub. Markel S, editor. PLoS
617 Comput Biol. 2016;12: e1004947. doi:10.1371/journal.pcbi.1004947

618 32. Lowndes JSS, Best BD, Scarborough C, Afflerbach JC, Frazier MR, O'Hara CC, et al. Our
619 path to better science in less time using open data science tools. Nature Ecology &
620 Evolution. 2017;1: 0160. doi:10.1038/s41559-017-0160

621 33. Bryan J. Excuse Me, Do You Have a Moment to Talk About Version Control? The
622 American Statistician. 2018;72: 20–27. doi:10.1080/00031305.2017.1399928

623 34. Foster C, Planella D, Gragnola J, Davis T. Issue and Kanban boards project management
624 guidelines. In: GitLab [Internet]. 2020 [cited 12 Mar 2021]. Available:
625 https://about.gitlab.com/handbook/marketing/project-management-guidelines/boards/

626 35. Schultheiss SJ. Ten Simple Rules for Providing a Scientific Web Resource. PLOS
627 Computational Biology. 2011;7: e1001126. doi:10.1371/journal.pcbi.1001126

628 36. Lee BD. Ten simple rules for documenting scientific software. PLOS Computational
629 Biology. 2018;14: e1006561. doi:10.1371/journal.pcbi.1006561

630 37. Taschuk M, Wilson G. Ten simple rules for making research software more robust. PLOS
631 Computational Biology. 2017;13: e1005412. doi:10.1371/journal.pcbi.1005412

632 38. Parker MS, Burgess AE, Bourne PE. Ten simple rules for starting (and sustaining) an
633 academic data science initiative. PLOS Computational Biology. 2021;17: e1008628.
634 doi:10.1371/journal.pcbi.1008628

635 39. Nüst D, Sochat V, Marwick B, Eglen SJ, Head T, Hirst T, et al. Ten simple rules for writing
636 Dockerfiles for reproducible data science. Markel S, editor. PLOS Computational Biology.
637 2020;16: e1008316. doi:10.1371/journal.pcbi.1008316

638 40. Framework for Open and Reproducible Research Training (FORRT). Welcome to FORRT.
639 In: Framework for Open and Reproducible Research Training (FORRT) [Internet]. 2021
640 [cited 12 Mar 2021]. Available: https://forrt.org/

641 41. rOpenSci. A guide to enhancing reproducibility in scientific results and writing. In:
642 Reproducibility in Science [Internet]. 2020 [cited 12 Mar 2021]. Available:
643 https://ropensci.github.io/reproducibility-guide/

644 42. Prlić A, Procter JB. Ten Simple Rules for the Open Development of Scientific Software.
645 PLOS Computational Biology. 2012;8: e1002802. doi:10.1371/journal.pcbi.1002802

646 43. Sandve GK, Nekrutenko A, Taylor J, Hovig E. Ten Simple Rules for Reproducible
647 Computational Research. PLOS Computational Biology. 2013;9: e1003285.
648 doi:10.1371/journal.pcbi.1003285

649 44. List M, Ebert P, Albrecht F. Ten Simple Rules for Developing Usable Software in
650 Computational Biology. PLOS Computational Biology. 2017;13: e1005265.
651 doi:10.1371/journal.pcbi.1005265

652 45. Helmy M, Crits-Christoph A, Bader GD. Ten Simple Rules for Developing Public
653 Biological Databases. PLOS Computational Biology. 2016;12: e1005128.
654 doi:10.1371/journal.pcbi.1005128

655 46. Bourne PE, Polka JK, Vale RD, Kiley R. Ten simple rules to consider regarding preprint
656 submission. PLOS Computational Biology. 2017;13: e1005473.
657 doi:10.1371/journal.pcbi.1005473

658 47. Mozilla. Best Practices Working Open. In: Open Leadership Training Series [Internet].
659 2020 [cited 12 Mar 2021]. Available: https://mozilla.github.io/open-leadership-training-
660 series/

661 48. Lowndes JSS. Audience building and strategic planning. In: Openscapes [Internet]. 2021
662 [cited 12 Mar 2021]. Available: https://www.openscapes.org/blog/2021/01/06/audience-
663 building/

664 49. Smith AM, Katz DS, Niemeyer KE. Software citation principles. PeerJ Comput Sci.
665 2016;2: e86. doi:10.7717/peerj-cs.86

666 50. Carlson D, Oda T. Editorial: Data publication – *ESSD* goals, practices and
667 recommendations. Earth System Science Data. 2018;10: 2275–2278. doi:10.5194/essd-10-
668 2275-2018

669

670

Supporting Information for

Ten Simple Rules for Researchers Who Want to Develop Web Apps

Sheila M. Saia[1], Natalie G. Nelson*[1,2], Sierra N. Young[1], Stanton Parham[1], Micah Vandegrift[3]

[1]Department of Biological and Agricultural Engineering, North Carolina State University, Raleigh, North Carolina, United States of America

[2]Center for Geospatial Analytics, North Carolina State University, Raleigh, North Carolina, United States of America

[3]North Carolina State University Libraries, North Carolina State University, Raleigh, North Carolina, United States of America

This manuscript was submitted to the PLOS Computational Biology "Ten Simple Rules" collection for peer review on March 18, 2021 and is being prepared for resubmission. This document is a preprint.

694 **File Continents:**

695 This file contains Text S1-S5 and Figures S1-S3.

696

697 *Number of Pages:* 19

698

699 **Contents Metadata:**

700 This document includes the supporting text and figures for this study as referred to in the main
701 text of the article. The associated manuscript is free to download per the *PLOS Computational*
702 *Biology* open access policy.

703

704

Text S1. First version of our request for proposals (RFP) contract "Scope of Work" section.

1. Scope of Work

The backend of the web application shall be created with Python (e.g. Django). The Contractor shall propose a framework or approach for the front-end of the application, as well as the SMS alert service. The proposal shall detail how testing is integrated in the development process, as well as how blocking bugs are identified and addressed early.

1.1 Features of the web application backend

- Pulls the NDFD Probability of Precipitation (PoP) and Quantitative Precipitation Forecast (QPF) products twice daily using the National Weather Service API; in the event that the National Weather Service API is down, the application shall post a notification on the web application interface.
- Calculates the probability of closure for each growing area in North Carolina (equations and values to be provided by the University).
- If the probability of closure exceeds a certain threshold, the application sends a SMS message and/or email to users based on their subscription preferences.
- Usage tracking (e.g. number of SMS messages sent, number of subscribers).

1.2 Features of the web application frontend (webpage)

- Description and history of web application.
- User registration: users submit contact information, shellfish growing areas, and notification preferences.
- User opt-out: users can unsubscribe from notifications.
- Map showing all shellfish growing areas in NC as well as closure probabilities. The university will supply the underlying files to create the map. The awarded contractor will create the map displayed on the application's frontend.

1.3 Open source requirements

The Python code used to create the web application must be open source. The web application will have either a GNU General Public License or Creative Commons Attribution 3.0 Unported (""CC-BY") License. The Contractor must comply with all U.S. Federal Open Data policies (see https://project-open-data.cio.gov/ for more details).

1.4 Timeline

Project starts: April 1, 2020

Fully functional application is developed and summary report due: June 30, 2020

Users test application: August 1, 2020 – September 30, 2021

Contractor receives requests for changes from the University: October 15, 2021

Contractor finalizes web application and submits final documentation: January 15, 2022

746 1.5 Progress Reporting
747 Awarded contractor will provide monthly progress reports via e-mail and video conferencing
748 with the university team responsible for this project. The university will set up the conference
749 calls monthly. Note any research data associated with this project must remain within the
750 contiguous United States of America.
751

Text S2. Final version of our request for proposals (RFP) contract "Scope of Work" section.

1. Scope of Work

The backend of the web application shall be created using a Linux, Apache, MySQL, PHP environment or an alternative open source framework that is compatible with goals outlined in Section 1.1 as well as the University's web hosting service. The Contractor shall propose an open-source framework for the frontend of the web application that is consistent with the goals outlined in Section 1.2. All code shall be committed to a GitHub repository created by the University. The Contractor shall use MailChimp as the SMS and email gateway. The University shall host and backup the web application (specifications outlined at https://oit.ncsu.edu/campus-it/web-services/). Costs associated with hosting and SMS/email alert notifications will be directly managed by the University and should not be included in the proposal budget. The proposal shall detail how testing is integrated in the development process, as well as how blocking bugs are identified and addressed early. The Contractor is expected to address web application bugs and updates from the project start date until January 15, 2022; the proposal should include an estimated cost to the University for any maintenance required over the duration of the project.

Draft wireframes of front-end pages are provided below. These wireframes are intended to communicate overall page structure, but the appearance shall adhere to the policies and standards outlined in Section 1.2 below. The awarded Contractor is encouraged to suggest aesthetic improvements to the overall design.

(We inserted wireframes here: see Figure S1.)

1.1 Features of the web application backend

- The University will write R and Python scripts to pull Probability of Precipitation (PoP) and Quantitative Precipitation Forecast (QPF) products from the National Weather Service (NWS) API (https://graphical.weather.gov/xml/rest.php), do calculations, and export results to the shellfish growing area closure probabilities table (see below). The tables will be used to update the web application frontend.
- R and Python scripts shall be scheduled to run every 12 hours for each shellfish growing area in North Carolina. If the NWS API is down, the web application shall display the most recent closure probabilities information along with the status of the NWS API server.
- If the maximum probability of closure in a 3-day window exceeds a certain threshold, the application shall send a plain text SMS and/or email alert notification to users based on their subscription preferences. When users subscribe to SMS notifications for multiple shellfish growing areas that are under alert, they shall receive one notification per shellfish growing area. For users who subscribe to email alert notifications for multiple shellfish growing areas that are under alert, they shall receive one consolidated email notification that includes all shellfish growing areas they subscribe to. SMS messages are expected to be approximately 50-75 characters long, e.g. "70% of closure in SGA A1 within next 3 days". SMS and email messages are expected to be sent in a timely manner.

- The web application database shall consist of the following tables and columns at a minimum:
    - Table: Subscriber contact information. Columns: Unique subscriber ID number, first name, last name, phone number, email address, date-time subscribed for SMS, date-time subscribed for emails, date-time unsubscribed to SMS, date-time unsubscribed to emails.
    - Table: User subscription preferences. Columns: Unique subscriber ID number, user first and last name, shellfish growing area, SMS (yes/no), email (yes/no). Records will repeat for each shellfish growing area a user subscribes to.
    - Table: Shellfish growing area closure probabilities. Columns: shellfish growing area, date-time, 3-day probability, 2-day probability, 1-day probability, color classification maximum probability in 3-day window, color classification for 3-day probability, color classification for 2-day probability, color classification for 1-day probability. This table shall log all calculated probabilities in individual rows; existing rows shall not be overwritten.
    - Table: Alert logging. Columns: Unique subscriber ID, date-time, alert type, shellfish growing area, third party SMS/email gateway confirmation, alert message plain text.
    - Table: Shellfish growing areas. Columns: Shellfish growing area, shellfish growing area status (approved, conditionally approved, prohibited), rainfall threshold, shellfish growing area shapefile path. Information populated in this table will be provided by the University and shall be readily editable by the University.
    - Table: Disclaimers. Columns: Disclaimer text, corresponding page on frontend. Disclaimer text will be provided by the University and shall be readily editable by the University.

1.2 Features of the web application frontend (web application)

The frontend shall be created with a technology that operates in a Linux Apache MySQL PHP environment.

- Main Landing Page: Includes header with the web application name and logo, which will be provided by the University; buttons for “Sign Up”, “Sign In”, and “About” pages; disclaimer text, which is pulled from the disclaimer table in the database; text showing the date and time when the probabilities and frontend were last updated; text explaining that those interested in receiving alert notifications should sign up. Below the header, a map overlaid on a widget or basemap occupies the majority of the page. The map shows all shellfish growing areas in North Carolina, and the shellfish growing area polygons are colored based on up-to-date closure probabilities. If a user selects a growing area, the name and closure probabilities (1-day, 2-day, 3-day) are shown. Users can toggle between 3-day, 2-day, and 1-day closure probability maps, with the max of the 1-, 2-, and 3-day probabilities set as the default (described as “closure probability within next 3 days”). Users can zoom in and out of the map. The University will supply all shellfish growing area spatial boundaries in one shapefile (.shp), as well as the metadata needed to create the map overlay. Closure probabilities shall be calculated on the backend and updated twice daily. Below the map, images and text are included to acknowledge organizations affiliated with the web application; the text and images will be provided by

the University and shall be editable. There is also a "Table View" button at the bottom of the page to view the Main Landing Page data as a sortable table.

- About: Description and history of the web application. Includes text and images, all of which will be provided by the University. The text and images shall be editable by the University. A "Back to Main Landing Page" button at the bottom of this page will return the user to the non-table view of the Main Landing Page.
- Sign Up: Users register using third-party social media accounts (Google and Facebook are required at a minimum). The Sign Up page pulls disclaimer text from the disclaimer table in the database. More details described in 3.2.5 below.
- Sign In: Users log in using a third-party social media account (Google and Facebook are required at a minimum) and can view their current account profile. The Sign In page pulls disclaimer text from the disclaimer table in the database. More details described in 3.2.5 below.
- User subscription preferences after Sign Up and Sign In: Once they sign up or sign in, users can view and/or make changes to their preferences. First name, last name, and email address are pulled from the third-party social media account and are not editable by the user. Phone number, alert notification preference (i.e., SMS and/or email), and shellfish growing areas shall be editable by the user. Users must enter a phone number to check that they want to receive SMS alert notifications and can choose to subscribe to multiple shellfish growing areas. A "Back to Main Landing Page" button at the bottom of this page will return the user to the non-table view of the Main Landing Page. The user subscription preferences page pulls disclaimer text from the disclaimer table in the database.
- Main Landing Page in Table View: Information presented on the main landing page (shellfish growing areas, probabilities of closure) shall be in a sortable table for easy viewing with screen readers and those who want to view the data in this format. Data to populate the table will come from the shellfish growing area closure probabilities table. A "Back to Main Landing Page" button at the bottom of this page will return the user to the non-table view of the Main Landing Page.
- Additional features: The web application shall meet the Revised Section 508 standards (https://www.access-board.gov/guidelines-and-standards/communications-and-it/about-the-ict-refresh/final-rule/text-of-the-standards-and-guidelines) incorporating the Web Content Accessibility Guidelines (WCAG) 2.0 A and AA. If possible, a current Voluntary Product Accessibility Template (VPAT) 2.0 or later detailing how this product will meet the aforementioned accessibility standards shall be provided. The web application shall meet the University's branding requirements (https://brand.ncsu.edu/). The web application shall utilize responsive design and be readily viewable on a mobile device. Each page of the web application shall incorporate Firebase analytics.

1.3 Open source requirements

All code used to create the web application shall be open source. The web application shall have either a GNU General Public License or Creative Commons Attribution 3.0 Unported (""CC-BY") License. The Contractor shall comply with all U.S. Federal Open Data policies (see https://project-open-data.cio.gov/ for more details).

1.4 Timeline

Project starts: April 1, 2020

Fully functional application is developed and summary report due: June 30, 2020

Users test application: August 1, 2020 – September 30, 2021

Contractor receives requests for changes from the University: October 15, 2021

Contractor finalizes web application and submits final documentation: January 15, 2022

1.5 Progress Reporting

Awarded Contractor will provide monthly progress reports via e-mail and video conferencing with the University team responsible for this project. The University will set up the conference calls monthly.

1. 6 Data and web application ownership

Note any research data associated with this project shall remain within the contiguous United States of America. *Ownership of all code, design, and databases shall be relinquished to the University.*

Text S3. "Phase 0" ShellCast user testing survey questions. Pre-test questions were administered before testing started and post-test questions were administered a week later, when web app testing was finished.

Pre-Test Questions

1. What browser did you use to view ShellCast? (multiple choice: Firefox, Safari, Chrome, Internet Explorer, other - fill in)
2. Where did you view ShellCast? (multiple choice: phone, tablet, computer, other - fill in)
3. To the best of your ability, please describe the purpose of ShellCast from memory. We ask that you write this response without returning to the About page because we're interested in learning which parts of the description stood out to you. (long answer)
4. To the best of your ability, please describe the information shown on the main landing page map from memory. We ask that you write this response without returning to the main landing page as we're interested in learning if the content on the map was memorable. (long answer)
5. At any point while reviewing the main landing page did you feel confused? (multiple choice: yes, no)
6. If you answered yes to question #5, please describe where and why you were confused? If you have to look back at ShellCast, please do. (long answer)
7. Did you interact with the map by clicking on growing areas? (multiple choice: yes, no, I'm not sure)
8. Did you interact with the map by clicking on 1-day, 2-day, and/or 3-day forecast options? (multiple choice: yes, no, I'm not sure)
9. At any point while reviewing the About page did you feel confused? (multiple choice: yes, no)
10. If you answered yes to question #9, please describe where and why you were confused? If you have to look back at ShellCast, please do. (long answer)
11. Did you encounter any difficulties when creating an account? (multiple choice: yes, no)
12. If you answered yes to question #11, please explain. (long answer)
13. Did you encounter any difficulties when adding leases? (multiple choice: yes, no)
14. If you answered yes to question #13, please explain. (long answer)
15. Overall, what is your opinion of the ShellCast web application? (Was the user interface simple, straightforward, and easy to use or complex, full of jargon and hard to understand?) (long answer)
16. Please suggest two or more ways we can improve the ShellCast web application. (long answer)
17. Please add any other comments or questions about the ShellCast web application. (Including typos, confusing words/wording, something isn't working properly, and additional functionality is needed.) (long answer)

Post-Test Questions

1. Did you choose to receive text message notifications for any of your leases? (multiple choice: yes, no)
2. If you answered yes to question #1, how many text message notifications did you receive over the course of the week? (short answer)
3. If you answered yes to question #1, what is your mobile phone service provider? (multiple choice: AT&T, Verizon, Sprint, other - fill in)
4. Did you choose to receive email notifications for any of your leases? (multiple choice: yes, no)
5. If you answered yes to question #4, how many email notifications did you receive over the course of the week? (short answer)
6. Did you use the link provided in the notification to return to the ShellCast web application? (multiple choice: yes, no, I'm not sure)
7. Describe two things you did not like about ShellCast. (long answer)
8. Describe two things you liked about ShellCast. (long answer)
9. Describe two things you are still confused about after using ShellCast. (long answer)
10. The term "1-day" was used in several places on the main page of ShellCast as well as in ShellCast notifications. What did the "1-day" forecast mean to you? (multiple choice: 1-day meant today, 1-day meant tomorrow, I'm not sure what 1-day meant, other - fill in)
11. The term "3-day" was used in several places on the main page of ShellCast as well as in ShellCast notifications. What did the "3-day" forecast mean to you? (multiple choice: 3-day meant a three-day period (cumulative), 3-day meant one day 3 days from now, I'm not sure what 3-day meant, other - fill in)
12. Overall, what is your opinion of the ShellCast notifications? (Were the notifications simple, straightforward, and easy to follow or complex, full of jargon and hard to understand?) (long answer)
13. Please suggest two or more ways we can improve ShellCast notifications. (long answer)
14. Please add any other comments or questions about the ShellCast notifications. (Including typos, confusing words/wording, something isn't working properly, and additional functionality is needed.) (long answer)

Text S4. "Phase 1" ShellCast user testing survey questions. Pre-test questions were administered before testing started and post-test questions were administered a week later, when web app testing was finished. Note: We included about half of the web app testers from "Phase 0" (Text S3) in the "Phase 1" round; the remaining half of testers were seeing ShellCast for the first time.

Pre-Test Questions

1. What browser did you use to view ShellCast? (multiple choice: Firefox, Safari, Chrome, Internet Explorer, other - fill in)
2. Where did you view ShellCast? (multiple choice: phone, tablet, computer, other - fill in)
3. To the best of your ability, please describe the purpose of ShellCast from memory. We ask that you write this response without returning to the About page because we're interested in learning which parts of the description stood out to you. (long answer)
4. To the best of your ability, please describe the information shown on the main landing page map from memory. We ask that you write this response without returning to the main landing page as we're interested in learning if the content on the map was memorable. (long answer)
5. At any point while reviewing the main landing page did you feel confused? (multiple choice: yes, no)
6. If you answered yes to question #5, please describe where and why you were confused? If you have to look back at ShellCast, please do. (long answer)
7. Did you interact with the map by clicking on growing areas? (multiple choice: yes, no, I'm not sure)
8. Did you interact with the map by clicking on 1-day, 2-day, and/or 3-day forecast options? (multiple choice: yes, no, I'm not sure)
9. At any point while reviewing the About page did you feel confused? (multiple choice: yes, no)
10. If so, please describe where and why you were confused? If you have to look back at ShellCast, please do. (long answer)
11. Did you watch the How ShellCast Works video? (multiple choice: yes, no)
12. If you answered yes to question #11, please describe if you found the video helpful or not helpful and describe why. (long answer)
13. Did you encounter any difficulties when creating an account? (multiple choice: yes, no)
14. If you answered yes to question #13, please explain. (long answer)
15. Did you encounter any difficulties when adding leases? (multiple choice: yes, no)
16. If you answered yes to question #15, please explain. (long answer)
17. Overall, what is your opinion of the ShellCast web application? (Was the user interface simple, straightforward, and easy to use or complex, full of jargon and hard to understand?) (long answer)
18. Please suggest two or more ways we can improve the ShellCast web application. (long answer)
19. Please add any other comments or questions about the ShellCast web application. (Including typos, confusing words/wording, something isn't working properly, and additional functionality is needed.) (long answer)

Post-Test Questions

1. Did you choose to receive text message notifications for any of your leases? (multiple choice: yes, no)
2. If you answered yes to question #1, how many text message notifications did you receive over the course of the week? (short answer)
3. If you answered yes to question #1, what is your mobile phone service provider? (multiple choice: AT&T, Verizon, Sprint, other - fill in)
4. Did you choose to receive email notifications for any of your leases? (multiple choice: yes, no)
5. If you answered yes to question #4, how many email notifications did you receive over the course of the week? (short answer)
6. Did you use the link provided in the notification to return to the ShellCast web application? (multiple choice: yes, no, I'm not sure)
7. Describe two things you did not like about ShellCast. (long answer)
8. Describe two things you liked about ShellCast. (long answer)
9. Describe two things you are still confused about after using ShellCast. (long answer)
10. The term "tomorrow" was used in several places on the main page of ShellCast as well as in ShellCast notifications. What did the "tomorrow" forecast mean to you? (multiple choice: the forecast for just tomorrow, the forecast for today and tomorrow combined, I'm not sure what "tomorrow" meant, other - fill in)
11. The term "in 2 days" was used in several places on the main page of ShellCast as well as in ShellCast notifications. What did the "in 2 days" forecast mean to you? (multiple choice: the forecast from today, tomorrow, and the next day combined; the forecast on a day that is 2 days from now; I'm not sure what "in 2 days" meant, other - fill in)
12. Overall, what is your opinion of the ShellCast notifications? (Were the notifications simple, straightforward, and easy to follow or complex, full of jargon and hard to understand?) (long answer)
13. Please suggest two or more ways we can improve ShellCast notifications. (long answer)
14. Please add any other comments or questions about the ShellCast notifications. (Including typos, confusing words/wording, something isn't working properly, and additional functionality is needed.) (long answer)

Text S5. ShellCast privacy policy.

Introduction

Last updated December 5, 2020

ShellCast ("we" or "us" or "our") respects the privacy of our users ("user" or "you"). This Privacy Policy explains how we collect, use, disclose, and safeguard your information when you visit our website https://go.ncsu.edu/shellcast, including any other media form, media channel, mobile website, or mobile application related or connected thereto (collectively, the "Site"). Please read this privacy policy carefully. If you do not agree with the terms of this privacy policy, please do not access the site.

We reserve the right to make changes to this Privacy Policy at any time and for any reason. We will alert you about any changes by updating the "Last Updated" date of this Privacy Policy. Any changes or modifications will be effective immediately upon posting the updated Privacy Policy on the Site, and you waive the right to receive specific notice of each such change or modification.

You are encouraged to periodically review this Privacy Policy to stay informed of updates. You will be deemed to have been made aware of, will be subject to, and will be deemed to have accepted the changes in any revised Privacy Policy by your continued use of the Site after the date such revised Privacy Policy is posted.

Collection of Your Information

We may collect information about you in a variety of ways. The information we may collect on the Site includes:

Personal Data

Personally identifiable information, such as your email address, telephone number, and mobile phone service provider, that you voluntarily give to us when you register with the Site. You are under no obligation to provide us with personal information of any kind, however your refusal to do so may prevent you from using certain features of the Site.

Google Permissions

If you choose to register with the Site through Google, then we will record the email address associated with your Google account.

Facebook Permissions

If you choose to register with the Site through Facebook, then we will record the email address associated with your Facebook account.

Use of Your Information

Having accurate information about you permits us to provide you with a smooth, efficient, and customized experience. Specifically, we may use information collected about you via the Site to:

- Assist law enforcement and respond to subpoena.
- Compile anonymous, aggregate statistical data and analysis for use internally or publicly.
- Create and manage your account.
- Email you regarding your account.
- Monitor and analyze usage and trends to improve your experience with the Site.
- Notify you of updates to the Site.
- Request feedback and contact you about your use of the Site.
- Send you notifications.

Disclosure of Your Information

We may share information we have collected about you in certain situations. Your information may be disclosed as follows:

By Law or to Protect Rights

If we believe the release of information about you is necessary to respond to legal process, to investigate or remedy potential violations of our policies, or to protect the rights, property, and safety of others, we may share your information as permitted or required by any applicable law, rule, or regulation. This includes exchanging information with other entities for fraud protection and credit risk reduction.

Third-Party Service Providers

We may share your information with third parties that perform services for us or on our behalf, including email delivery and hosting services.

Third-Party Websites

The Site may contain links to third-party websites and applications of interest that are not affiliated with us. Once you have used these links to leave the Site, any information you provide to these third parties is not covered by this Privacy Policy, and we cannot guarantee the safety and privacy of your information. Before visiting and providing any information to any third-party websites, you should inform yourself of the privacy policies and practices (if any) of the third party responsible for that website, and should take those steps necessary to, in your discretion, protect the privacy of your information. We are not responsible for the content or privacy and security practices and policies of any third parties, including other sites, services or applications that may be linked to or from the Site.

Security of Your Information

We use administrative, technical, and physical security measures to help protect your personal information. While we have taken reasonable steps to secure the personal information you provide to us, please be aware that despite our efforts, no security measures are perfect or impenetrable, and no method

of data transmission can be guaranteed against any interception or other type of misuse. Any information disclosed online is vulnerable to interception and misuse by unauthorized parties. Therefore, we cannot guarantee complete security if you provide personal information.

Policy For Children

We do not knowingly solicit information from or market to children under the age of 13. If you become aware of any data we have collected from children under age 13, please contact us using the contact information provided at the end of this document.

Controls For Do-Not-Track Features

Most web browsers and some mobile operating systems include a Do-Not-Track ("DNT") feature or setting you can activate to signal your privacy preference not to have data about your online browsing activities monitored and collected. No uniform technology standard for recognizing and implementing DNT signals has been finalized. As such, we do not currently respond to DNT browser signals or any other mechanism that automatically communicates your choice not to be tracked online. If a standard for online tracking is adopted that we must follow in the future, we will inform you about that practice in a revised version of this Privacy Policy. Most web browsers and some mobile operating systems include a Do-Not-Track ("DNT") feature or setting you can activate to signal your privacy preference not to have data about your online browsing activities monitored and collected. If you set the DNT signal on your browser, we will respond to such DNT browser signals.

Options Regarding Your Information

Account Information

You may at any time review or change the information in your account or terminate your account by:

- Logging into your account settings and updating your account.
- Contacting us using the contact information provided at the end of this document.

Upon your request to terminate your account, we will deactivate or delete your account and information from our active databases. However, some information may be retained in our files to prevent fraud, troubleshoot problems, assist with any investigations, enforce our Terms of Use and/or comply with legal requirements.

Emails and Communications

If you no longer wish to receive correspondence, emails, or other communications from us, you may opt-out by:

- Noting your preferences at the time you register your account with the Site.
- Logging into your account settings and updating your preferences.
- Contacting us using the contact information provided at the end of this document.

If you no longer wish to receive correspondence, emails, or other communications from third parties, you are responsible for contacting the third party directly.

California Privacy Rights

California Civil Code Section 1798.83, also known as the "Shine The Light" law, permits our users who are California residents to request and obtain from us, once a year and free of charge, information about categories of personal information (if any) we disclosed to third parties for direct marketing purposes and the names and addresses of all third parties with which we shared personal information in the immediately preceding calendar year. If you are a California resident and would like to make such a request, please submit your request in writing to us using the contact information provided at the end of this document.

If you are under 18 years of age, reside in California, and have a registered account with the Site, you have the right to request removal of unwanted data that you publicly post on the Site. To request removal of such data, please contact us using the contact information provided at the end of this document, and include the email address associated with your account and a statement that you reside in California. We will make sure the data is not publicly displayed on the Site, but please be aware that the data may not be completely or comprehensively removed from our systems.

Contact Us

If you have questions or comments about this Privacy Policy, please contact us at: shellcastapp@ncsu.edu

Figure S1. ShellCast wireframes, including (a) main page map view when user is not signed in, (b) main page table view, (c) ShellCast "About" page, (d) user login page, (e) user notifications/profile page, (f) main page map view when user is signed in (can see lease pin and click pin to see lease-specific information.

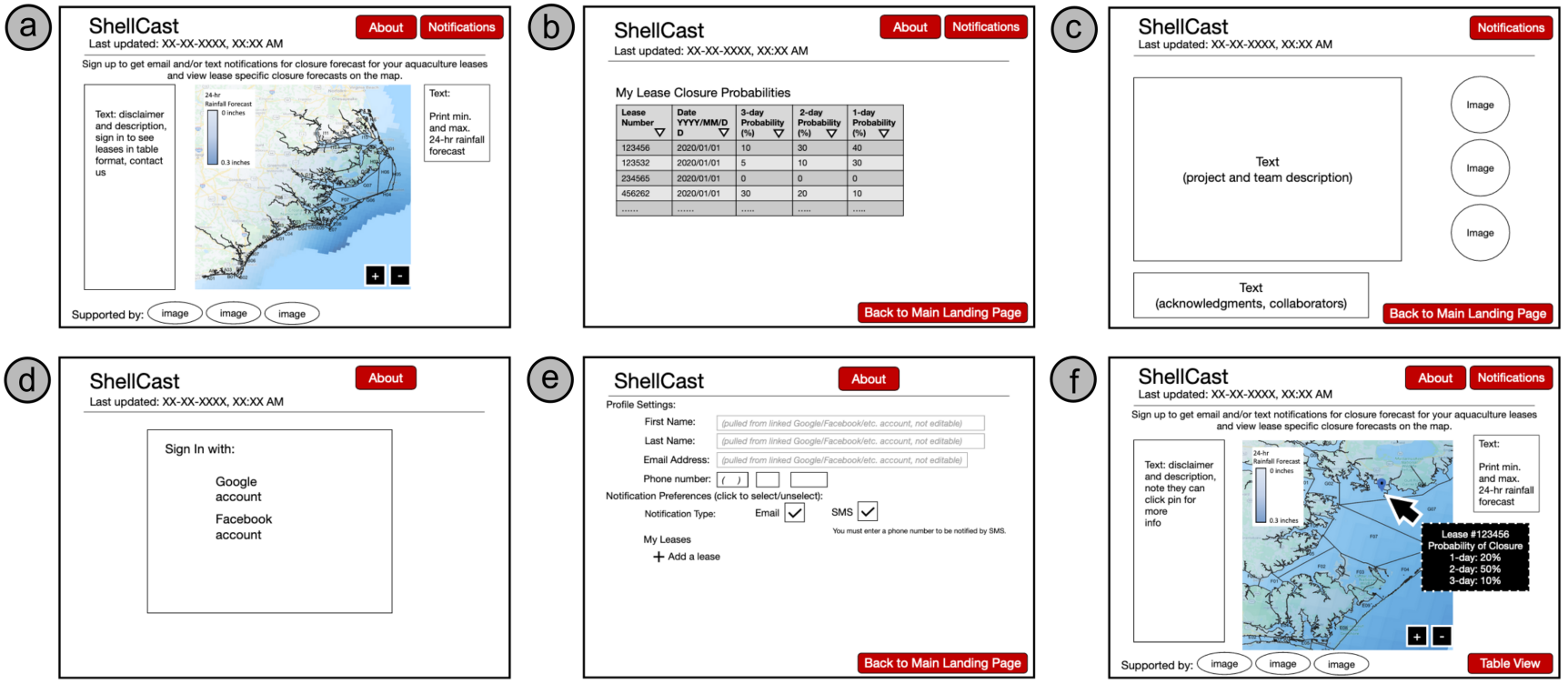

Figure S2. Screenshot of the ShellCast GitHub project page depicting web app issues and their status (i.e., “To Do”, “In Progress”, “Done”, “Wishlist”).

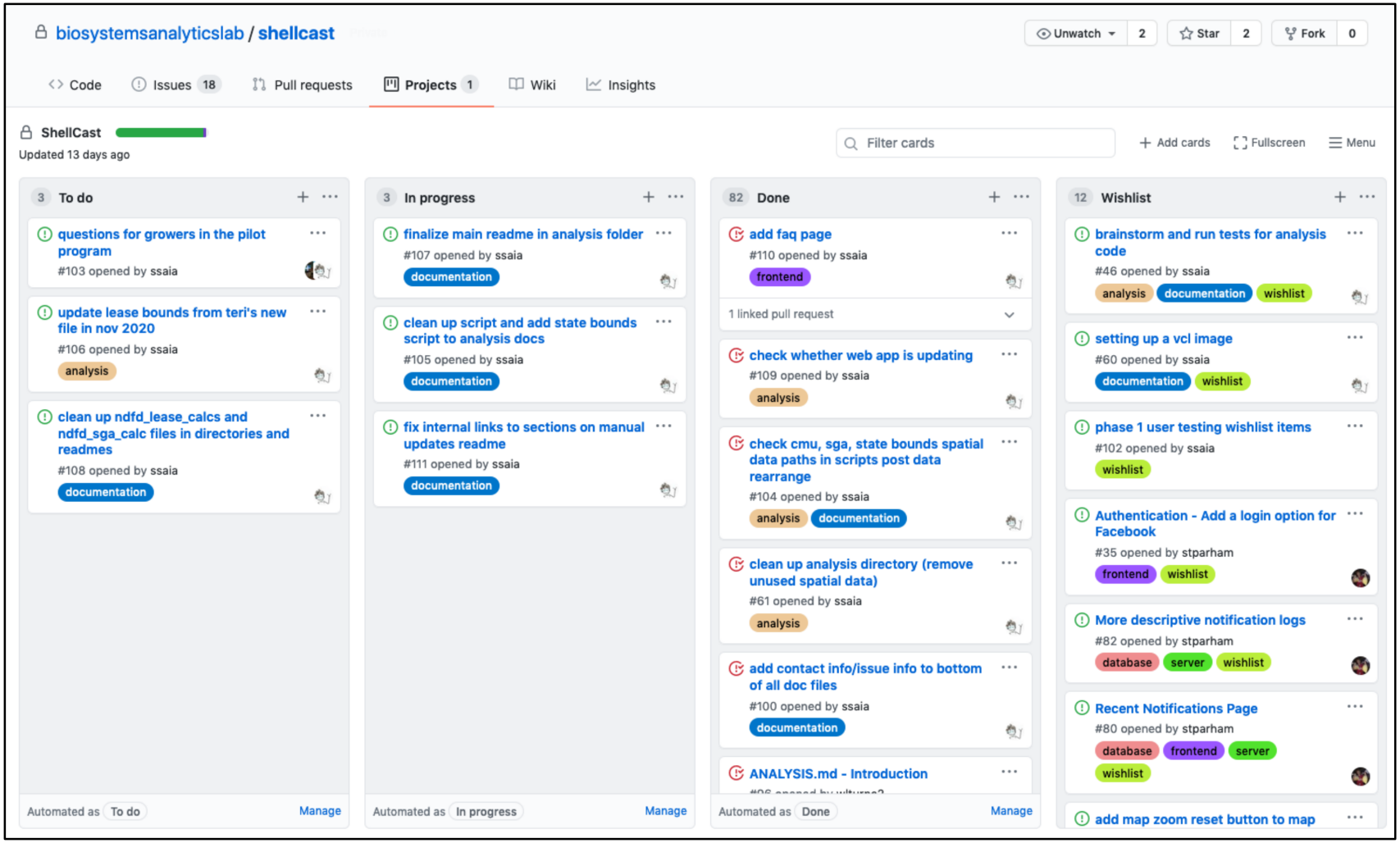

Figure S3. Screenshot of the ShellCast main page with lease map pin, lease forecast pop-up, and table view.