Applied & Translational Genomics 6 (2015) 35–41

Contents lists available at ScienceDirect

Applied & Translational Genomics

journal homepage: www.elsevier.com/locate/atg

Widening participation would be key in enhancing bioinformatics and genomics research in Africa

Thomas K. Karikari [a,b,*], Emmanuel Quansah [c,d], Wael M.Y. Mohamed [e]

[a] Neuroscience, School of Life Sciences, University of Warwick, Coventry CV4 7AL, UK
[b] Midlands Integrative Biosciences Training Partnership, University of Warwick, Coventry CV4 7AL, UK
[c] Pharmacology, Faculty of Health and Life Sciences, De Montfort University, Leicester LE1 9BH, UK
[d] Department of Molecular Biology and Biotechnology, School of Biological Science, University of Cape Coast, Cape Coast, Ghana
[e] Clinical Pharmacology Department, Menoufia Medical School, Menoufia University, Egypt

ARTICLE INFO

Keywords:
Africa
Bioinformatics
Genomics
Computational biology
Biomedical research
Agriculture

ABSTRACT

Bioinformatics and genome science (BGS) are gradually gaining roots in Africa, contributing to studies that are leading to improved understanding of health, disease, agriculture and food security. While a few African countries have established foundations for research and training in these areas, BGS appear to be limited to only a few institutions in specific African countries. However, improving the disciplines in Africa will require pragmatic efforts to expand training and research partnerships to scientists in yet-unreached institutions. Here, we discuss the need to expand BGS programmes in Africa, and propose mechanisms to do so.

1. Introduction

Bioinformatics and genome science (BGS) are relatively new disciplines, gaining importance across the biomedical research, healthcare and agriculture sectors due to their importance in helping to improve the timeliness and accuracy of disease diagnosis, prognosis and treatment, as well as enhancing crop yield (Machuka, 2004; McCarthy et al., 2013; Worku et al., 2005). While scientifically-advanced countries in North America and Europe have been major leaders in BGS, many developing countries (including some African countries) have made important achievements in applying genomics technologies to enhance biomedical research, healthcare and agriculture (Machuka, 2004; Mitropoulos et al., 2015). Since the mid-1990s, many African countries have been employing tools and techniques in BGS to help advance scientific research (Bishop et al., 2015; Fatumo et al., 2014; Karikari, 2015a; Lyantagaye, 2013; Masiga and Isokpehi, 2004; Ojo and Omabe, 2011). BGS research groups have been constituted and studies employing these approaches have been conducted and published by African scientists, helping to improve our understanding of the biological basis of health and disease among humans and non-human species (Bishop et al., 2015; Fatumo et al., 2014; H3Africa Consortium et al., 2014; Karikari, 2015a; Machuka, 2004). Importantly, scientists in Africa have been applying BGS techniques to address some of the continent's most debilitating challenges, including those of food insecurity, unsustainable agricultural practices and the high disease burden (Fatumo et al., 2014; Karikari, 2015a; Machuka, 2004). For example, some African scientists and their collaborators recently employed genomics technologies to sequence the genome of the tsetsefly, the vector for Human African trypanosomiasis — a devastating tropical disease (International Glossina Genome Initiative, 2014). Also, African researchers were instrumental in the epidemiological characterisation of the Ebola virus disease (EVD) (through whole-genome sequencing) during the recent outbreak in West Africa (Gire et al., 2014). A major progress in agricultural genomics in Africa was the sequencing of the sorghum genome in 2009 and the recent sequencing of the genomes of forty-four sorghum lines, which demonstrated that genomics diversity and historical domestication differences existed between the lines studied (Mace et al., 2013; Paterson et al., 2009). Sorghum is a nutrient-rich African crop, with a promise to help improve food security and reduce malnutrition and poverty on the continent (Kelemu et al., 2013). Being the first indigenous crop in Africa to have had its genome completely sequenced, the findings from these studies provide a vital resource for genetic improvement of sorghum and other cereal crops to enhance crop yield, agricultural productivity and food security (Kelemu et al., 2013). The foregoing examples show that the importance of BGS is becoming widespread and almost indispensable to advancing biological research in Africa.

2. BGS in Africa appear to be concentrated in a few institutions

The progress made in BGS in Africa can be attributed to investments made in building the physical and intellectual capacity to promote the

* Corresponding author at: Neuroscience, School of Life Sciences, University of Warwick, Coventry CV4 7AL, UK.
E-mail addresses: T.K.Karikari@warwick.ac.uk (T.K. Karikari), quansahmanuel@yahoo.com (E. Quansah), wmy107@gmail.com (W.M.Y. Mohamed).

http://dx.doi.org/10.1016/j.atg.2015.09.001
2212-0661/

Table 1
Academic, commercial and non-profit organisations in Africa that have bioinformatics and genomics resources and expertise.[a]

Institution	Focus	Website
African Centre of Excellence in Bioinformatics, University of Sciences, Techniques, and Technology of Bamako, Mali	Providing infrastructure and tools for training, mentorship and research in large-scale bioinformatics and genomics data analysis.	–
African Centre of Excellence for Genomics of Infectious Diseases, Redeemer's University, Nigeria	To apply genomics and bioinformatics approaches to help improve research into infectious disease pathogenesis, surveillance, clinical care and control.	http://acegid.org
African Centre for Gene Technologies, South Africa	To develop a network of scientists with expertise in biotechnology and *omics* technologies.	http://www.acgt.co.za
African Collaborative Centre for Microbiome and Genomics Research, Institute of Human Virology, Nigeria	To develop a collaborative team of expert scientists who will help to accelerate the search for disease biomarkers that would increase the timeliness and accuracy of cervical cancer research, diagnosis and treatment.	http://h3accme.com
West African Bioethics, Nigeria	The programme is aimed at providing training and research in bioethics (delivered in English and French) to scientists in West Africa. Moreover, West African Bioethics has introduced graduate programmes (MSc, MPhil and PhD) in bioethics in partnership with the University of Ibadan, Nigeria.	http://bioethicscenter.net/web/
Institut Pasteur de Côte d'Ivoire (IPCI), Côte d'Ivoire	The IPCI has expertise in the use of molecular technologies for studying pathogens of public health importance — particularly in the areas of diagnosis, genotyping and genomics.	http://www.pasteur.ci
Biosciences Eastern and Central Africa (BECA), International Livestock Research Institute (ILRI), Kenya	BECA is a New Partnership for African Development (NEPAD) initiative that supports the expansion of bioinformatics training and research efforts in East and Central Africa.	http://hub.africabiosciences.org; http://www.ilri.org/kenya
West African Bioinformatics Research Institute, Ilorin, Nigeria	This non-profit organisation is aimed at helping to promote bioinformatics teaching and research in West Africa, through the development of databases and software and the provision of training courses.	http://www.wabri.org
African Studies on Population and Health (ASOPAH), Nigeria	This non-profit organisation is an affiliate of the Environmental and Health of Communities of Africans international organisation. ASOPAH's research focus includes genetic factors in health and disease.	http://www.asopah.org
H3ABioNet nodes (these are centres of excellence in bioinformatics funded under the H3Africa scheme)		
Botswana Harvard AIDS Institute Partnership, Botswana	This is a research partnership between the Government of Botswana and Harvard University in the United States to improve research and training efforts aimed at controlling the HIV/AIDS epidemic in Botswana and elsewhere in southern Africa.	http://aids.harvard.edu/reserch/bhp/
Egyptian Center of Bioinformatics and Genomics/Genetics Department, Faculty of Agriculture, Zagazig University, Egypt	The Centre focuses on providing bioinformatics and genomics research and education support to members of the Zagazig University community and beyond.	http://english.zu.edu.eg/Index.aspx; http://www.agri.zu.edu.eg (in Arabic)
Kumasi Centre for Collaborative Research in Tropical Medicine/Kwame Nkrumah University of Science and Technology, Ghana	This H3Africa node has expertise for research and training in bioinformatics and genomics, with a focus on infectious, non-communicable and neglected tropical diseases.	http://kccr-ghana.org; https://www.knust.edu.gh
Noguchi Memorial Institute for Medical Research, Ghana	This node has expertise in molecular and computational research methods (including quantitative PCR, probe hybridisation techniques, and genome sequencing and data analysis).	http://www.noguchimedres.org
International Centre of Insect Physiology and Ecology (ICIPE) , Kenya	Bioinformatics and genomics research at ICIPE is focused on infectious diseases, anthropods and plant-parasite interactions.	http://www.icipe.org
International Center of Excellence in Research, University of Sciences, Techniques and Technology of Bamako, USTTB, Mali	The Centre has expertise in, and resources for, research and education in malaria, neglected tropical diseases, HIV/AIDS and tuberculosis.	http://www.usttb.edu.ml
Southern Africa Network for Biosciences (SANBio), University of Mauritius, Mauritius	SANBio aims to train more scientists in southern Africa in bioinformatics skills through capacity-building courses and efforts to introduce bioinformatics modules into existing university curricula.	http://www.uom.ac.mu
Centre de Recherche Medicale et Sanitaire, Niamey (CERMES), Niger	CERMES aims to develop a centre of excellence in bioinformatics to provide support in research and training in public health and other areas in Mali.	http://www.cermes.net/cermes/
Covenant University Bioinformatics Research (CUBRe), Nigeria	CUBRe aims to help advance bioinformatics in Nigeria through research and capacity-building activities targeted at supporting academic and corporate organisations to improve biomedical research and drug discovery and development.	http://cubre.covenantuniversity.edu.ng
National Biotechnology Development Agency (NABDA), Nigeria	NABDA seeks to develop national competence in the development and application of bioinformatics tools and techniques to provide biotechnology-driven solutions to biological problems in Nigeria.	http://www.nabda.gov.ng

Centre for Proteomic and Genomic Research, South Africa	The bioinformatics focus of this company lies in the application of *omics* technologies to solve biological questions, particularly in the areas of pharmacogenomics and personalised medicine.	http://www.cpgr.org.za
Computational Biology Group, Institute for Infectious Disease and Molecular Medicine, Faculty of Heath Sciences, University of Cape Town, South Africa	This research group supports the expansion of bioinformatics activities at the University of Cape Town through the provision of research and training activities.	http://www.cbio.uct.ac.za
Research Unit in Bioinformatics (RUBi), Department of Biochemistry and Microbiology, Rhodes University, South Africa	The RUBi node specialises in the use and development of bioinformatics tools and techniques for drug discovery and agriculture.	https://rubi.ru.ac.za
South African National Bioinformatics Institute (SANBI)/Medical Research Council of South Africa Bioinformatics Unit, University of the Western Cape, South Africa	Aside from internal research and training activities, the SANBI node supports the H3ABioNet network in: (i) collecting and analysing data on capacity-building activities within the network; (ii) the development of a harmonised procedure for conducting genome sequencing data analysis; (iii) supporting network members in the collection and storage of clinical information on study participants; and (iv) the development and implementation of bioinformatics training activities.	http://www.sanbi.ac.za
University of Pretoria, South Africa	Bioinformatics and genomics expertise here focuses on immunogenomics, plant genomics, malaria and breast cancer.	http://www.up.ac.za
University of the Free State, South Africa	This group focuses on the application of molecular and bioinformatics approaches for genomics and proteomics studies.	http://www.ufs.ac.za
University of the Witwatersrand, South Africa	This node specialises in bioinformatics teaching, research and service provision in the areas of genome-wide association studies, population structure and computing.	http://www.bioinf.wits.ac.za
Centre for Bioinformatics, Future University of Sudan/University of Khartoum, Sudan	The Centre aims to coordinate the development of bioinformatics capacity-building and research efforts in Sudan.	http://www.futureu.edu.sd; http://www.uofk.edu
Management and Development for Health, Tanzania	This non-profit organisation focuses on helping to improve public health research and services in Tanzania. Major targets include common diseases such as malaria, infectious diseases, non-communicable diseases and child health.	http://mdh-tz.org
Muhimbili University of Health and Allied Sciences, Tanzania	This node has major interests and expertise in sickle cell disease research and education.	http://www.muhas.ac.tz
University of Dar es Salaam, Tanzania	To build capacity in the use of crosscutting technologies in bioinformatics for scientific research.	https://www.udsm.ac.tz
Uganda Virus Research Institute, Uganda	Virology research and education, particularly disease aetiology, molecular mechanisms, prevention and control.	http://www.uvri.go.ug
Malawi-Liverpool-Wellcome Trust Clinical Research Programme, Malawi	Research and education under this programme is focused on building the capacity of scientists and clinicians in Malawi to address high-burden diseases in the country.	http://www.mlw.medcol.mw
Centre Regional de Transfusion Sanguine de Rabat, Morocco	This H3ABioNet node supports research and training activities in the application of bioinformatics and genomics to improve hematology services in Morocco.	–
Ecole National des Sciences Appliquees, Abdekmalek Essaadi University, Tangier (ENSA), Morocco	Bioinformatics and genomics expertise at ENSA includes molecular genetics, transcriptomics, proteomics, and computational database design and data analysis.	http://www.ensat.ac.ma/Portail/
Faculte de Medecine et de Pharmacie de Rabat, Universite Mohammed V Souissi (FMPR), Morocco	The FMPR node combines expertise in genomics, biotechnology and epidemiology. There are plans to establish graduate programmes in biotechnology in the near future.	http://www.medramo.ac.ma
Faculty of Science, University Mohammed V of Rabat, Morocco	The focus here is on genomics, immunogenetics, and immunoinformatics.	http://www.um5a.ac.ma/index.php/en/
Institut National d'Hygiène, Morocco	Research at this Institute is aimed at deciphering the molecular basis of tropical diseases and also to improve food safety and hygiene practices.	–
Institut National de Recherche Agronomique, Morocco	To use bioinformatics and genomics approaches in improving agricultural practices and food security.	http://www.inra.org.ma/
Institute Pasteur du Maroc, Morocco	The aim of this Institute is to conduct research and provide training in public health, particularly in environmental health and food safety.	http://www.pasteur.ma
Institute Pasteur of Tunis, Tunisia	This national public health institute is mandated to conduct research and training that are geared towards safeguarding human and animal health.	http://www.pasteur.tn
University Mohammed First (UMP)	To conduct training and research in bioinformatics and related areas.	http://www.ump.ma/?lang=en

[a] This list is indicative and may not provide a full account of all bioinformatics and genomics centres in Africa. Further details about some of the centres listed here have been previously provided (Bishop et al., 2015; Fatumo et al., 2014; Folarin et al., 2014; H3Africa Consortium et al., 2014; Karikari, 2015a). Concerning H3ABioNet nodes, only those that are based at African institutions have been profiled. Websites accessed 15th July, 2015.

disciplines (Adoga et al., 2014; Fatumo et al., 2014; H3Africa Consortium et al., 2014; Karikari, 2015a). Notable among these are the recent capacity-building efforts of the Human Heredity and Health in Africa (H3Africa) Consortium, the H3ABioNet continent-wide bioinformatics network and The World Bank (Table 1); these programmes have been discussed elsewhere (Adoga et al., 2014; Bishop et al., 2015; Folarin et al., 2014; Karikari, 2015a). In Africa, many of the BGS capacity-building efforts till date have focussed on strengthening the scientific capacity in leading universities and research institutes (Bishop et al., 2015; H3Africa Consortium et al., 2014; Karikari, 2015a). For example, since its establishment in 1996, the South African National Bioinformatics Network, the first BGS-related scientific network in Africa, established regional nodes (centres of excellence) at leading institutions to develop BGS activities in the country (Bishop et al., 2015; Masiga and Isokpehi, 2004). More recently, H3ABioNet established nodes mostly at African institutions with BGS capacities to influence the development of the field (Bishop et al., 2015; H3Africa Consortium et al., 2014). According to data from Webometrics (http://www.webometrics.info), a leading academic ranking initiative, most of these nodes are located at highly-ranked institutions (in their respective countries). Rightly, locating nodes at leading institutions provides opportunities for intra- and inter-institutional partnerships aimed at propagating BGS activities. However, while this may be an excellent approach to facilitate the expansion of the disciplines, it seems that activities of this nature mostly favour scientists who have been previously exposed to BGS, leaving behind those who may have no appreciation of these areas yet. For instance, although the H3ABioNet nodes and other scientific organisations do organise training programmes for African scientists (Bishop et al., 2015; Karikari, 2015a), these programmes often require applicants to have some level of basic or intermediate understanding in specific topics, a requirement that naturally favours applicants from institutions where BGS activities can be found. Although foundation courses are also sometimes offered, only a limited number of applicants can be accepted onto such courses. Furthermore, the existing BGS courses are often held in the cities, which is a disadvantage to scientists based at rural institutions due to transportation problems and general lack of funding.

Consequently, BGS research output on the continent is dominated by, and is almost limited to, institutions with existing capacities. For example, BGS-related publications in Ghana over the past decade have been produced by scientists affiliated to a few research and higher education institutions (RHEIs); these institutions are mostly highly-ranked (Karikari, 2015a). The situation is not different in Nigeria where only twenty research groups working on BGS-related themes have been identified, mostly in the country's best ranked institutions (Fatumo et al., 2014). While BGS are relatively new research areas in Africa, strategies should be devised to ensure that their introduction becomes more equitable and not skewed to only a few institutions, in order to prevent future imbalances.

3. Why should participation in BGS be widened?

For a more effective BGS development in Africa, special attention should be paid to widening participation to include yet-unreached institutions especially those in rural areas with peculiar challenges (Karikari, 2015a). Scientists based in rural RHEIs are strategically positioned to help advance BGS applications in Africa. This is because the use of BGS on the continent has focused mainly on research in biomedical science and agriculture, which are areas of prime importance and challenge to rural communities (Fatumo et al., 2014; Karikari, 2015a). While the agricultural industry is concentrated in rural Africa, many healthcare challenges (including neglected tropical diseases and malaria) are also acute in rural areas, making them an important focus for genomics research and bioinformatics applications. With regard to this, the recent EVD outbreak started from a rural community in Guinea, but due to the poor nature of rural healthcare and research systems, ended up spreading and killing several people in West Africa and even affected others in Europe and North America (imported cases) (Centre for Disease Control and Prevention, USA, 2015). This is a clear example supporting the opinion that the widening gap between rural scientists and their counterparts elsewhere must be addressed.

Favourable conditions for BGS activities have been improving in Africa (Bishop et al., 2015; Karikari, 2015a; Ojo and Omabe, 2011). BGS have been recognised as effective routes for bringing modern science to many areas of Africa mainly due to the following reasons: (i) the relatively less expensive infrastructural and training requirements compared to similar activities conducted in wet laboratory-intensive disciplines (ii) increasing Internet speed and penetration rates (iii) increasing affordability of genome sequencing and other high-throughput technologies, and (iv) improved access to BGS-related public databases and open source software, ensuring the efficient use of scarce funding opportunities (Bishop et al., 2015; Karikari, 2015a; Ojo and Omabe, 2011).

Empowering rural institutions for BGS research would have many potential advantages such as helping to improve (i) disease diagnosis, characterisation and treatment (ii) swift responses to public health emergencies (iii) studies into neglected tropical diseases (iv) food security through the use of genomics tools to increase crop yield, and (v) biology and health education (Karikari, 2015a; Worku et al., 2005). BGS approaches such as genome-wide association studies and next generation sequencing (NGS) have been used in clinical applications such as cancer treatment selection based on molecular tumour characterisation (Ong et al., 2012) and real-time monitoring of infectious disease outbreaks (Anderson et al., 2014). In the area of infectious diseases, genome sequencing approaches have been instrumental to control outbreaks in tuberculosis, severe acute respiratory syndrome (SARS), cholera, H1N1 influenza, methicillin-resistant *Staphylococcus aureus* (MERS), carbapenem-resistant *Klebsiella pneumoniae* and EVD (Anderson et al., 2014; Chin et al., 2011; Gardy et al., 2011; Gire et al., 2014; Marra et al., 2003; Ong et al., 2012; Smith et al., 2009; Snitkin et al., 2012). For instance, sequencing of the genome of microorganism isolates from affected patients enabled scientists to identify the coronavirus causative agent in the 2003 SARS outbreak (Marra et al., 2003). Also, the fact that the genomes of disease-causing microorganisms can be sequenced within a short timeframe makes sequencing technologies important tools in clinical disease surveillance and control (McCarthy et al., 2013). An example is the recent application of whole genome sequencing to identify and analyse the source of MERS infection in an American football team (Anderson et al., 2014). This timely use of NGS tools helped to avoid a large-scale disease outbreak.

Presently, the demand for BGS workforce in Africa outstrips the supply; this shortage suggests that expanding training partnerships could be a good means of addressing the deficit (Karikari, 2015a; Ojo and Omabe, 2011). In fact, the scientific workforce, such as healthcare professionals, are willing to improve their use and application of computer-based technologies, should the needed training and support be provided (Ruxwana et al., 2010; Sukums et al., 2014). In the section that follow, we will discuss suggested ways for expanding BGS activities in Africa.

4. Suggested approaches for expanding BGS research in Africa

First, scientific societies should organise more outreach programmes specifically to train scientists in rural RHEIs in BGS. Initially, these programmes should focus on providing foundational tuition to trainees without any background in BGS, and later move on to intermediate and advanced levels. This would ensure that the needs of both scientists who would like to obtain expert training in BGS and those seeking to familarise themselves with specific skills and knowledge that are pertinent to their research activities would be attended to. Preferably, the training activities should be brought to the doorstep of the beneficiaries to ensure maximum patronage. Training could focus on experimental genomics as well as how to analyse genomics and related data using bioinformatics tools (especially using open source tools). These activities would have many potential benefits such as empowering trainee scientists to employ BGS tools and techniques to study human, plant and animal health and disease, and analyse research data from these areas. Since scientists at rural institutions are in proximity to rural residents, training them would also help to ensure that rural indigenous knowledge (RIK) is better applied in BGS research activities and is also better catered for in the development of ethical, legal and social implications (ELSI) guidelines for BGS research (Worku et al., 2005). Without adequate understanding of RIK and cooperation of the key community leaders, the effective application of BGS in Africa will be challenging (Ngueng-Feze et al., 2011). In addition, BGS training can influence student training by ensuring that more students in rural RHEIs benefit from the introduction of BGS modules and degree programmes (Karikari, 2015b). Presently, only a handful of institutions in a few African countries do provide bioinformatics degree courses, with only a few others offering bioinformatics modules as part of life science degree programmes (Bishop et al., 2015; Fatumo et al., 2014; Karikari, 2015a). Improving the provision of BGS training in African universities would be an important step in widening participation in the disciplines (Karikari, 2015a). Although the H3ABioNet is leading efforts to expand and harmonise BGS training (such as through the establishment of a bioinformatics education committee and the provision of outreach programmes), more stakeholders should get involved (Bishop et al., 2015; Karikari, 2015a).

Second, training programmes could be organised for rural health workers to help them apply BGS approaches to improve the diagnosis, characterisation and treatment of common diseases such as infectious, non-communicable and neglected tropical diseases (Karikari and Aleksic, 2015). The reduced cost of genome sequencing technologies provides an opportunity for more health institutions in Africa to get involved in genomics research (Karikari, 2015a). Healthcare in rural Africa is poor, and the integration of genomics and bioinformatics technologies can help to improve disease diagnosis and treatment outcomes (Drislane et al., 2014; Karikari and Aleksic, 2015). Previous attempts at integrating indigenous and orthodox healthcare systems in Africa have proved highly successful (Ngueng-Feze et al., 2011). Since scientists and healthcare professionals working in rural areas are close to these disadvantaged populations, empowering them to employ BGS tools and techniques for disease-related research would be beneficial in identifying how environmental factors possibly affect health outcomes at the community level. For example, this would help to improve the effectiveness of public health surveillance and the identification of disease risk factors, advancing disease diagnosis and treatment in a timely manner. Moreover, BGS provide the opportunity to further study the usefulness of traditional and herbal medical products in Africa for healthcare purposes, for instance, by screening bioactive compounds for their potential disease-modifying benefits and identifying their molecular mechanisms of action (Karikari and Aleksic, 2015; Karikari and Quansah, 2015).

Third, training more African agricultural scientists in modern BGS techniques could play a key role in improving food security, leading to sustainable economic growth (Machuka, 2004). For example, rural development activities such as eco-tourism can benefit from increased understanding of genetics and genomics; agricultural genomics can be used to integrate RIK and local community practices into biodiversity conservation (Worku et al., 2005). Moreover, the efficient application of techniques and tools in plant genomics, systems biology and animal agricultural genomics would be beneficial in increasing agricultural yield and food security and reducing post-harvest losses (Machuka, 2004). Therefore, the triangulation of bioinformatics, genomics and RIK would serve to harness vital community-based knowledge to promote agriculture and food security (Machuka, 2004; Worku et al., 2005). Presently, the focus of BGS capacity-building efforts in Africa seems to have been tilted towards biomedical and health research compared to agriculture and industrial biotechnology (Fatumo et al., 2014; Karikari, 2015a). However, the potential benefits of BGS are not limited to biomedical and health research. More research and training support programmes in BGS dedicated to agriculture, industrial biotechnology and related areas (similar to the H3Africa scheme for health research) are therefore needed.

Furthermore, the implementation of BGS technologies has social implications which have not been adequately studied in Africa (Wright et al., 2014). RIK plays significant roles in shaping the ELSI of genomics and bioinformatics studies (Tindana et al., 2012; Wright et al., 2014). Training scientists in rural areas can help to improve this situation by promoting dialogue with community members using culturally acceptable means, and promoting their informed consent and optimum participation in research (Tindana et al., 2012).

Lastly, African governments, policymakers, educational authorities and funding agencies should improve their support for science research and education, especially those that apply BGS. Although scientific output in Africa has improved over the past decade, there is a concern about the long-term sustainability of this improvement because scientific research in the continent is overly reliant on donor support, since most countries have no local arrangements to fund research work through competitive funding schemes (Karikari, 2015a; Karikari and Quansah, 2015; The World Bank, 2014). With the exception of South Africa that provides public funding for genomics research, most African countries lack this kind of support system (Pohlhaus and Cook-Deegan, 2008). This is evident in the fact that most BGS resource centres in Africa are funded by international donor agencies. This makes it difficult for African researchers and governments to control their research agenda, because international funders may dictate research direction (Nordling, 2015). African governments need to better appreciate that effective scientific research contributes to economic and social growth (Karikari et al., 2015). Therefore, for Africa's quest for accelerated economic, social and industrial growth to become a reality, governments will need to improve their investments in local scientific research (Irikefe et al., 2011).

5. Conclusion

Although BGS have been integrated into biomedical and agricultural research in Africa, training and research in these areas need to be strategically expanded to yet-unreached institutions and scientists in order to better propagate the disciplines. Scientific organisations should develop more practical approaches to train and support scientists in such institutions for research in BGS to help improve education, agriculture and healthcare. Governments, educational authorities, policymakers and funding organisations should also do more to support the expansion of BGS initiatives within the continent.

Abbreviations

BGS bioinformatics and genome science
ELSI ethical, legal and social implications
EVD Ebola virus disease
H3ABioNet a pan-African bioinformatics network funded through H3Africa
H3Africa Human Heredity of Health in Africa
MERS methicillin-resistant *Staphylococcus aureus*
RHEI research and higher education institution
RIK rural indigenous knowledge
SARS severe acute respiratory syndrome

Competing interests

The authors declare that there is no conflict of interest.

Acknowledgements

TKK was funded by the Biotechnology and Biological Sciences Research Council (BBSRC; http://www.bbsrc.ac.uk) grant number BB/J014532/1, through the Midlands Integrative Biosciences Training Partnership. EQ was supported by a doctoral studentship from De Montfort University, Leicester, UK. TKK acknowledges support from the Research Councils UK (RCUK) Block Grant at the University of Warwick for the payment of open access fee. The funders had no role in the decision to publish or preparation of the manuscript.

References

Adoga, M.P., Fatumo, S.A., Agwale, S.M., 2014. H3Africa: a tipping point for a revolution in bioinformatics, genomics and health research in Africa. Source Code Biol. Med. 9, 10. http://dx.doi.org/10.1186/1751-0473-9-10.

Anderson, D.J., Harris, S.R., Godofsky, E., Toriscelli, T., Rude, T.H., Elder, K., Sexton, D.J., Pellman, E.J., Mayer, T., Fowler, V.G., Peacock, S.J., 2014. Whole genome sequencing of a methicillin-resistant *Staphylococcus aureus* pseudo-outbreak in a professional football team. Open Forum Infect. Dis. 1, ofu096. http://dx.doi.org/10.1093/ofid/ofu096.

Bishop, Ö.T., Adebiyi, E.F., Alzohairy, A.M., Everett, D., Ghedira, K., Ghouila, A., Kumuthini, J., Mulder, N.J., Panji, S., Patterton, H.-G., 2015. Bioinformatics education—perspectives and challenges out of Africa. Brief. Bioinform. 16 (2), 355–364. http://dx.doi.org/10.1093/bib/bbu022.

Centres for Disease Control and Prevention, USA, 2015. 2014 Ebola outbreak in West Africa — case counts [WWW document]. (URL http://www.cdc.gov/vhf/ebola/outbreaks/2014-west-africa/case-counts.html).

Chin, C.-S., Sorenson, J., Harris, J.B., Robins, W.P., Charles, R.C., Jean-Charles, R.R., Bullard, J., Webster, D.R., Kasarskis, A., Peluso, P., Paxinos, E.E., Yamaichi, Y., Calderwood, S.B., Mekalanos, J.J., Schadt, E.E., Waldor, M.K., 2011. The origin of the Haitian cholera outbreak strain. N. Engl. J. Med. 364, 33–42. http://dx.doi.org/10.1056/NEJMoa1012928.

Drislane, F.W., Akpalu, A., Wegdam, H.H.J., 2014. The medical system in Ghana. Yale J. Biol. Med. 87, 321–326.

Fatumo, S.A., Adoga, M.P., Ojo, O.O., Oluwagbemi, O., Adeoye, T., Ewejobi, I., Adebiyi, M., Adebiyi, E., Bewaji, C., Nashiru, O., 2014. Computational biology and bioinformatics in Nigeria. PLoS Comput. Biol. 10, e1003516. http://dx.doi.org/10.1371/journal.pcbi.1003516.

Folarin, O.A., Happi, A.N., Happi, C.T., 2014. Empowering African genomics for infectious disease control. Genome Biol. 15, 515. http://dx.doi.org/10.1186/s13059-014–0515-y.

Gardy, J.L., Johnston, J.C., Sui, S.J.H., Cook, V.J., Shah, L., Brodkin, E., Rempel, S., Moore, R., Zhao, Y., Holt, R., Varhol, R., Birol, I., Lem, M., Sharma, M.K., Elwood, K., Jones, S.J.M., Brinkman, F.S.L., Brunham, R.C., Tang, P., 2011. Whole-genome sequencing and social-network analysis of a tuberculosis outbreak. N. Engl. J. Med. 364, 730–739. http://dx.doi.org/10.1056/NEJMoa1003176.

Gire, S.K., Goba, A., Andersen, K.G., Sealfon, R.S.G., Park, D.J., Kanneh, L., Jalloh, S., Momoh, M., Fullah, M., Dudas, G., Wohl, S., Moses, L.M., Yozwiak, N.L., Winnicki, S., Matranga, C.B., Malboeuf, C.M., Qu, J., Gladden, A.D., Schaffner, S.F., Yang, X., Jiang, P.-P., Nekoui, M., Colubri, A., Coomber, M.R., Fonnie, M., Moigboi, A., Gbakie, M., Kamara, F.K., Tucker, V., Konuwa, E., Saffa, S., Sellu, J., Jalloh, A.A., Kovoma, A., Koninga, J., Mustapha, I., Kargbo, K., Foday, M., Yillah, M., Kanneh, F., Robert, W., Massally, J.L.B., Chapman, S.B., Bochicchio, J., Murphy, C., Nusbaum, C., Young, S., Birren, B.W., Grant, D.S., Scheiffelin, J.S., Lander, E.S., Happi, C., Gevao, S.M., Gnirke, A., Rambaut, A., Garry, R.F., Khan, S.H., Sabeti, P.C., 2014. Genomic surveillance elucidates Ebola virus origin and transmission during the 2014 outbreak. Science 345, 1369–1372. http://dx.doi.org/10.1126/science.1259657.

H3Africa Consortium, Rotimi, C., Abayomi, A., Abimiku, A., Adabayeri, V.M., Adebamowo, C., Adebiyi, E., Ademola, A.D., Adeyemo, A., Adu, D., Affolabi, D., Agongo, G., Ajayi, S., Akarolo-Anthony, S., Akinyemi, R., Akpalu, A., Alberts, M., Alonso Betancourt, O., Alzohairy, A.M., Ameni, G., Amodu, O., Anabwani, G., Andersen, K., Arogundade, F., Arulogun, O., Asogun, D., Bakare, R., Balde, N., Baniecki, M.L., Beiswanger, C., Benkahla, A., Bethke, L., Boehnke, M., Boima, V., Brandful, J., Brooks, A.I., Brosius, F.C., Brown, C., Bucheton, B., Burke, D.T., Burnett, B.G., Carrington-Lawrence, S., Carstens, N., Chisi, J., Christoffels, A., Cooper, R., Cordell, H., Crowther, N., Croxton, T., de Vries, J., Derr, L., Donkor, P., Doumbia, S., Duncanson, A., Ekem, I., Sayed, A., El, Engel, M.E., Enyaru, J.C.K., Everett, D., Fadlelmola, F.M., Fakunle, E., Fischbeck, K.H., Fischer, A., Folarin, O., Gamieldien, J., Garry, R.F., Gaseitsiwe, S., Gbadegesin, R., Ghansah, A., Giovanni, M., Goesbeck, P., Gomez-Olive, F.X., Grant, D.S., Grewal, R., Guyer, M., Hanchard, N.A., Happi, C.T., Hazelhurst, S., Hennig, B.J., Hertz-, C., Fowler Hide, W., Hilderbrandt, F., Hugo-Hamman, C., Ibrahim, M.E., James, R., Jaufeerally-Fakim, Y., Jenkins, C., Jentsch, U., Jiang, P.-P., Joloba, M., Jongeneel, V., Joubert, F., Kader, M., Kahn, K., Kaleebu, P., Kapiga, S.H., Kassim, S.K., Kasvosve, I., Kayondo, J., Keavney, B., Kekitiinwa, A., Khan, S.H., Kimmel, P., King, M.-C., Kleta, R., Koffi, M., Kopp, J., Kretzler, M., Kumuthini, J., Kyobe, S., Kyobutungi, C., Lackland, D.T., Lacourciere, K.A., Landouré, G., Lawlor, R., Lehner, T., Lesosky, M., Levitt, N., Littler, K., Lombard, Z., Loring, J.F., Lyantagaye, S., Macleod, A., Madden, E.B., Mahomva, C.R., Makani, J., Mamven, M., Marape, M., Mardon, G., Marshall, P., Martin, D.P., Masiga, D., Mason, R., Mate-Kole, M., Matovu, E., Mayige, M., Mayosi, B.M., Mbanya, J.C., McCurdy, S.A., McCarthy, M.I., McIlleron, H., Mc'Ligeyo, S.O., Merle, C., Mocumbi, A.O., Mondo, C., Moran, J.V., Motala, A., Moxey-Mims, M., Mpoloka, W.S., Msefula, C.L., Mthiyane, T., Mulder, N., Mulugeta, G.h., Mumba, D., Musuku, J., Nagdee, M., Nash, O., Ndiaye, D., Nguyen, A.Q., Nicol, M., Nkomazana, O., Norris, S., Nsangi, B., Nyarko, A., Nyirenda, M., Obe, E., Obiakor, R., Oduro, A., Ofori-Acquah, S.F., Ogah, O., Ogendo, S., Ohene-Frempong, K., Ojo, A., Olanrewaju, T., Oli, J., Osafo, C., Ouwe Missi Oukem-Boyer, O., Ovbiagele, B., Owen, A., Owolabi, M.O., Owolabi, L., Owusu-Dabo, E., Pare, G., Parekh, R., Patterton, H.G., Penno, M.B., Peterson, J., Pieper, R., Plange-Rhule, J., Pollak, M., Puzak, J., Ramesar, R.S., Ramsay, M., Rasooly, R., Reddy, S., Sabeti, P.C., Sagoe, K., Salako, T., Samassékou, O., Sandhu, M.S., Sankoh, O., Sarfo, F.S., Sarr, M., Shaboodien, G., Sidibe, I., Simo, G., Simuunza, M., Smeeth, L., Sobngwi, E., Soodyall, H., Sorgho, H., Sow Bah, O., Srinivasan, S., Stein, D.J., Susser, E.S., Swanepoel, C., Tangwa, G., Tareila, A., Tastan Bishop, O., Tayo, B., Tiffin, N., Tinto, H., Tobin, E., Tollman, S.M., Traoré, M., Treadwell, M.J., Troyer, J., Tsimako-Johnstone, M., Tukei, V., Ulasi, I., Ulenga, N., van Rooyen, B., Wachinou, A.P., Waddy, S.P., Wade, A., Wayengera, M., Whitworth, J., Wideroff, L., Winkler, C.A., Winnicki, S., Wonkam, A., Yewondwos, M., Sen, T., Yozwiak, N., Zar, H., 2014. Research capacity. Enabling the genomic revolution in Africa. Science 344, 1346–1348. http://dx.doi.org/10.1126/science.1251546.

International Glossina Genome Initiative, 2014. Genome sequence of the tsetse fly (*Glossina morsitans*): vector of African trypanosomiasis. Science 344, 380–386. http://dx.doi.org/10.1126/science.1249656.

Irikefe, V., Vaidyanathan, G., Nordling, L., Twahirwa, A., Nakkazi, E., Monastersky, R., 2011. Science in Africa: the view from the front line. Nat. News 474, 556–559. http://dx.doi.org/10.1038/474556a.

Karikari, T.K., 2015a. Bioinformatics in Africa: the rise of Ghana? PLoS Comput Biol 11 (9), e1004308. http://dx.doi.org/10.1371/journal.pcbi.1004308.

Karikari, T.K., 2015b. Letter to the editor. J. Microbiol. Biol. Educ. 16 (1), 3–4. http://dx.doi.org/10.1128/jmbe.v16i1.801.

Karikari, T.K., Aleksic, J., 2015. Neurogenomics: an opportunity to integrate neuroscience, genomics and bioinformatics research in Africa. Appl. Transl. Genomics. 5, 3–10. http://dx.doi.org/10.1016/j.atg.2015.06.004.

Karikari, T.K., Cobham, A.E., Ndams, I.S., 2015. Building sustainable neuroscience capacity in Africa: the role of non-profit organisations. Metab. Brain Dis. http://dx.doi.org/10.1007/s11011-015-9687-8.

Karikari, T.K., Quansah, E., 2015. Neurogenomics: challenges and opportunities for Ghana. Appl. Transl. Genomics 5, 11–14. http://dx.doi.org/10.1016/j.atg.2015.06.002.

Kelemu, S., Gebrekidan, B., Harvey, J., 2013. Bringing the benefits of sorghum genomics to Africa. In: Paterson, A.H. (Ed.), Genomics of the Saccharinae. Plant Genetics and Genomics, Crops and Models. Springer New York, pp. 519–540.

Lyantagaye, S.L., 2013. Current status and future perspectives of bioinformatics in Tanzania. Tanzan. J. Sci. 39, 1–11.

Mace, E.S., Tai, S., Gilding, E.K., Li, Y., Prentis, P.J., Bian, L., Campbell, B.C., Hu, W., Innes, D.J., Han, X., Cruickshank, A., Dai, C., Frère, C., Zhang, H., Hunt, C.H., Wang, X., Shatte, T., Wang, M., Su, Z., Li, J., Lin, X., Godwin, I.D., Jordan, D.R., Wang, J., 2013. Whole-genome sequencing reveals untapped genetic potential in Africa's indigenous cereal crop sorghum. Nat. Commun. 4. http://dx.doi.org/10.1038/ncomms3320.

Machuka, J., 2004. Agricultural genomics and sustainable development: perspectives and prospects for Africa. Afr. J. Biotechnol. 3, 127–135.

Marra, M.A., Jones, S.J.M., Astell, C.R., Holt, R.A., Brooks-Wilson, A., Butterfield, Y.S.N., Khattra, J., Asano, J.K., Barber, S.A., Chan, S.Y., Cloutier, A., Coughlin, S.M., Freeman, D., Girn, N., Griffith, O.L., Leach, S.R., Mayo, M., McDonald, H., Montgomery, S.B., Pandoh, P.K., Petrescu, A.S., Robertson, A.G., Schein, J.E., Siddiqui, A., Smailus, D.E., Stott, J.M., Yang, G.S., Plummer, F., Andonov, A., Artsob, H., Bastien, N., Bernard, K., Booth, T.F., Bowness, D., Czub, M., Drebot, M., Fernando, L., Flick, R., Garbutt, M., Gray, M., Grolla, A., Jones, S., Feldmann, H., Meyers, A., Kabani, A., Li, Y., Normand, S., Stroher, U., Tipples, G.A., Tyler, S., Vogrig, R., Ward, D., Watson, B., Brunham, R.C., Krajden, M., Petric, M., Skowronski, D.M., Upton, C., Roper, R.L., 2003. The genome sequence of the SARS-associated coronavirus. Science 300, 1399–1404. http://dx.doi.org/10.1126/science.1085953.

Masiga, D.K., Isokpehi, R.D., 2004. Opportunities in Africa for training in genome science. Afr. J. Biotechnol. 3, 117–122.

McCarthy, J.J., McLeod, H.L., Ginsburg, G.S., 2013. Genomic medicine: a decade of successes, challenges, and opportunities. Sci. Transl. Med. 5. http://dx.doi.org/10.1126/scitranslmed.3005785 (189 sr4–189 sr4).

Mitropoulos, K., Jaibeji, H.A., Forero, D.A., Laissue, P., Wonkam, A., Lopez-Correa, C., Mohamed, Z., Chantratita, W., Lee, M.T., Llerena, A., Brand, A., Ali, B.R., Patrinos, G.P., 2015. Success stories in genomic medicine from resource-limited countries. Hum. Genomics 9, 11. http://dx.doi.org/10.1186/s40246-015-0033-3.

Ngueng-Feze, I., Borda-Rodriguez, A., Huzair, F., 2011. Not so simple: situating postgenomics personalized medicine in the regional context in Africa for global and womens health. Curr. Pharmacogenomics Pers. Med. 9, 332–334. http://dx.doi.org/10.2174/187569211798377171.

Nordling, L., 2015. Research: Africa's fight for equality. Nature 521, 24–25. http://dx.doi.org/10.1038/521024a.

Ojo, O.O., Omabe, M., 2011. Incorporating bioinformatics into biological science education in Nigeria: prospects and challenges. Infect. Genet. Evol. 11, 784–787. http://dx.doi.org/10.1016/j.meegid.2010.11.015.

Ong, F.S., Das, K., Wang, J., Vakil, H., Kuo, J.Z., Blackwell, W.-L.B., Lim, S.W., Goodarzi, M.O., Bernstein, K.E., Rotter, J.I., Grody, W.W., 2012. Personalized medicine and pharmacogenetic biomarkers: progress in molecular oncology testing. Expert. Rev. Mol. Diagn. 12, 593–602. http://dx.doi.org/10.1586/erm.12.59.

Paterson, A.H., Bowers, J.E., Bruggmann, R., Dubchak, I., Grimwood, J., Gundlach, H., Haberer, G., Hellsten, U., Mitros, T., Poliakov, A., Schmutz, J., Spannagl, M., Tang, H., Wang, X., Wicker, T., Bharti, A.K., Chapman, J., Feltus, F.A., Gowik, U., Grigoriev, I.V., Lyons, E., Maher, C.A., Martis, M., Narechania, A., Otillar, R.P., Penning, B.W., Salamov, A.A., Wang, Y., Zhang, L., Carpita, N.C., Freeling, M., Gingle, A.R., Hash, C.T., Keller, B., Klein, P., Kresovich, S., McCann, M.C., Ming, R., Peterson, D.G., Mehboob-ur-Rahman, Ware, D., Westhoff, P., Mayer, K.F.X., Messing, J., Rokhsar, D.S., 2009. The *Sorghum bicolor* genome and the diversification of grasses. Nature 457, 551–556. http://dx.doi.org/10.1038/nature07723.

Pohlhaus, J.R., Cook-Deegan, R.M., 2008. Genomics research: world survey of public funding. BMC Genomics 9, 472. http://dx.doi.org/10.1186/1471-2164-9-472.
Ruxwana, N.L., Herselman, M.E., Conradie, D.P., 2010. ICT applications as e-health solutions in rural healthcare in the Eastern Cape Province of South Africa. HIM J. 39, 17–26.
Smith, G.J.D., Vijaykrishna, D., Bahl, J., Lycett, S.J., Worobey, M., Pybus, O.G., Ma, S.K., Cheung, C.L., Raghwani, J., Bhatt, S., Peiris, J.S.M., Guan, Y., Rambaut, A., 2009. Origins and evolutionary genomics of the 2009 swine-origin H1N1 influenza A epidemic. Nature 459, 1122–1125. http://dx.doi.org/10.1038/nature08182.
Snitkin, E.S., Zelazny, A.M., Thomas, P.J., Stock, F., NISC Comparative Sequencing Programgroup, Henderson, D.K., Palmore, T.N., Segre, J.A., 2012. Tracking a hospital outbreak of carbapenem-resistant *Klebsiella pneumoniae* with whole-genome sequencing. Sci. Transl. Med. 4, 148ra116. http://dx.doi.org/10.1126/scitranslmed.3004129.
Sukums, F., Mensah, N., Mpembeni, R., Kaltschmidt, J., Haefeli, W.E., Blank, A., 2014. Health workers' knowledge of and attitudes towards computer applications in rural African health facilities. Glob. Health Action 7, 24534.
The World Bank, 2014. A Decade of Development in sub-Saharan African Science, Technology, Engineering and Mathematics Research.
Tindana, P., Bull, S., Amenga-Etego, L., de Vries, J., Aborigo, R., Koram, K., Kwiatkowski, D., Parker, M., 2012. Seeking consent to genetic and genomic research in a rural Ghanaian setting: a qualitative study of the MalariaGEN experience. BMC Med. Ethics 13, 15. http://dx.doi.org/10.1186/1472-6939-13-15.
Worku, M., Thompson, A., Gray, B., 2005. Indigenous knowledge, bioinformatics and rural agriculture. Presented at the 9th ICABR International Conference on Agricultural Biotechnology: Ten Years Later. Italy, Ravello.
Wright, G.E., Adeyemo, A.A., Tiffin, N., 2014. Informed consent and ethical re-use of African genomic data. Hum. Genomics 8, 18. http://dx.doi.org/10.1186/s40246-014-0018-7.