



Cite this: *Chem. Commun.*, 2019, 55, 8651

Received 24th May 2019,
Accepted 25th June 2019

DOI: 10.1039/c9cc04011k

rsc.li/chemcomm

Cu-Catalyzed highly selective reductive functionalization of 1,3-diene using H_2O as a stoichiometric hydrogen atom donor[†]

Qifan Li,^a Xiaoyang Jiao,^a Mimi Xing,^a Penglin Zhang,^a Qian Zhao^a and Chun Zhang  ^{a,b}

A copper-catalyzed highly regio- and diastereo-selective reductive reaction of terminal 1,3-diene with water and aldehyde has been developed. This chemistry afforded a product containing a terminal alkenyl group, which is a versatile kind of precursor for organic synthesis, with the scope for various substrates. The present reaction system could realize the catalytic transfer of hydrogen to diene using water as a stoichiometric H atom donor. In this transformation, B_2Pin_2 , a mild and practical kind of reductant was used as the mediator. The reaction pathway of this practical strategy was illustrated by a control experiment.

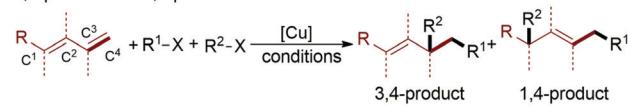
Developing new organic transformation strategies to preserve an active functional group is important for the synthesis of drugs, natural products and functional material molecules.¹ Among a lot of versatile starting compounds, 1,3-diene has caught more and more attention, because the difunctionalization of a conjugated diene with high regio- and diastereo-selectivity is an important type of transformation, which allows the controlled formation of multiple complex isomeric products from a simple precursor.^{2,3} In recent years, copper-catalyzed reaction systems have been extensively applied in such reactions, owing to the low price of copper-catalysts, ambient reaction conditions or practical reaction protocols.⁴ With such a powerful strategy, the terminal diene can be converted into a 1,4- or 3,4-functionalized product with good selectivity (1, Scheme 1). Compared with the above synthetic strategy, we have developed a novel copper-catalyzed B_2Pin_2 mediated highly regio- and diastereo-selective functionalization of terminal 1,3-diene to afford a 1,2-functionalized product (2, Scheme 1).

In contrast to other metal reagents, the organic boron-reagent is much more stable, and practical as it reacts under ambient

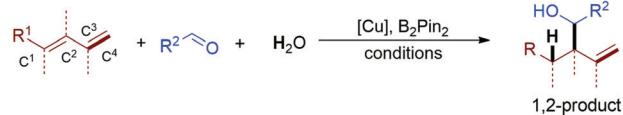
conditions, so the preparation of this kind of compound has been studied intensely.⁵ Among these methods, the hydroboration of dienes affords important boron reagents, which are powerful intermediates in many transformations.⁶ However, some air or moisture sensitive reagents and catalysts, such as $Ni(cod)_2$ or $HBPin$, are usually used for these reactions. The present transformation results in the formation of an allyl boron intermediate with good regioselectivity using a copper-salt/ H_2O / B_2Pin_2 system, which makes this method more practical. Importantly, examples of the catalytic transfer hydrogenation of simple alkenes using H_2O as the stoichiometric H atom donor show that it is a sustainable strategy for organic synthesis.⁷ Our work exploits a new way of using H_2O as a safe and cost-efficient hydrogen atom source for a highly selective catalytic reductive transformation process.

Our study commenced with the copper-catalyzed reaction of (*E*)-buta-1,3-dien-1-ylbenzene (**1a**), benzaldehyde (**2a**), B_2Pin_2 and H_2O . Interestingly, this practical one-pot reaction afforded 2-benzyl-1-phenylbut-3-en-1-ol (**3aa**) with 76% yield and 5:1 diastereoselectivity (entry 1, Table 1 and ESI[†]). The efficiency of this reaction decreased when other kinds of bases were used, such as $NaO^t\text{-Bu}$, $KO^t\text{-Bu}$, or $LiOMe$ (entries 1–4, Table 1 and ESI[†]). We then surveyed the effect of different solvents. Compared with THF, 1,4-dioxane induced low yield and selectivity, but toluene and DCE afforded much better results (entries 5 to 7, Table 1).

1). Previous work: Cu-catalyzed functionalization of terminal 1,3-diene to make 3,4-product and 1,4-product



2). This work: The strategy to make terminal alkenyl group reserved product



Scheme 1 Functionalization of terminal 1,3-diene.

^a Department of Chemistry, Tianjin Key Laboratory of Molecular Optoelectronic Science, School of Sciences, Institute of Molecular Plus, Tianjin University, Weijin Rd. 92, Tianjin 300072, China. E-mail: chunzhang@tju.edu.cn

^b State Key Laboratory of Elemento-Organic Chemistry, Nankai University, Tianjin 300071, China

[†] Electronic supplementary information (ESI) available. See DOI: 10.1039/c9cc04011k

Table 1 The effect of different reaction conditions^a

Entry	Solvent	Base	[Cu]	Yield ^b (%)	dr	1a	2a	[Cu] (10 mol%), PPh ₃ (11 mol%) Base (2.0 equiv), B ₂ Pin ₂ (2.0 equiv) H ₂ O (3.0 equiv), solvent (1.5 mL), N ₂	3aa		
						Ph	Ph	H	Ph	HO	Ph
1	THF	LiO ^t -Bu	Cu(OTf) ₂	76	5:1						
2	THF	NaO ^t -Bu	Cu(OTf) ₂	52	4:1						
3	THF	KO ^t -Bu	Cu(OTf) ₂	69	5:1						
4	THF	LiOMe	Cu(OTf) ₂	66	2:1						
5	1,4-Dioxane	LiO ^t -Bu	Cu(OTf) ₂	64	4:1						
6	Toluene	LiO ^t -Bu	Cu(OTf) ₂	80	9:1						
7	DCE	LiO ^t -Bu	Cu(OTf) ₂	93	>20:1						
8	DCE	LiO ^t -Bu	Cu(acac) ₂	76	>20:1						
9	DCE	LiO ^t -Bu	CuCl	78	>20:1						
10	DCE	LiO ^t -Bu	CuOAc	23	13:1						
11 ^c	DCE	LiO ^t -Bu	Cu(OTf) ₂	0	—						
12	DCE	LiO ^t -Bu	None	0	—						

^a 1a (0.25 mmol), 2a (0.5 mmol), B₂Pin₂ (0.5 mmol), base (0.5 mmol), cat (10 mol%), PPh₃ (11 mol%), H₂O (3.0 equiv.), solvent (1.5 mL).

^b Isolated yield, diastereomers are inseparable, dr was determined by ¹H-NMR. ^c Without B₂Pin₂.

In particular, when DCE was chosen as a solvent, the product could be obtained with 93% yield and better than 20:1 diastereoselectivity (entry 7, Table 1). Further studies indicated that different kinds of copper-salts affected the result of this reaction (entries 8 to 10, Table 1). Among them, Cu(OTf)₂ was the best choice. The data for entries 11 and 12 proved that this reaction did not proceed without a copper catalyst or B₂Pin₂ (Table 1).

Using H₂O as a hydrogen atom donor and B₂Pin₂ as a mediator for this reductive transformation, the substrate scope of terminal 1,3-diene was investigated (Table 2). In general, modest to good yields and diastereoselectivity using either electron-rich (MeO- and Me₂N-), or electron-deficient (F-, CF₃- and Cl-) aryl substituted 1,3-diene were observed (3aa to 3ka, Table 2). And, substituents at the *ortho*-position of the arene group did not affect the efficiency (3ba, Table 2). Notably, when bromo-substituted aromatic 1,3-diene was employed as a substrate, the corresponding product was afforded in 95% yield with great selectivity, which could be used for further transformation (3ja, Table 2). The iodo-substituted aromatic 1,3-diene still worked, but with lower efficiency (3ka, Table 2). To our delight, the naphthyl, furyl and thiienyl groups survived under these reductive reaction conditions (3la to 3na, Table 2). Importantly, alkyl 1,3-diene was smoothly transformed into the corresponding products (3oa to 3ra, Table 2). The 1,2-disubstituted 1,3-diene still worked well, giving a product containing a quaternary carbon atom (3ra, Table 2).

The substrate scope of the Cu-catalyzed B₂Pin₂ mediated highly selective reductive transformation was further expanded to a variety of substituted aldehydes (2) (Table 3). These results indicated that aryl aldehyde with both electron-donating and electron-withdrawing groups proceeded well with good yields and great diastereoselectivity (3aa to 3ap, Table 3). Substrate groups at the *para*-, *meta*-, and *ortho*-positions of the arene ring did not affect the efficiency (3ab to 3ad, Table 3). Notably, even

Table 2 Cu-Catalyzed B₂Pin₂ mediated reductive reaction of 2a with different terminal 1,3-dienes (1)^a

1	2a	Cu(OTf) ₂ (10 mol%), PPh ₃ (11 mol%) LiOBu (2.0 equiv), B ₂ Pin ₂ (2.0 equiv) H ₂ O (3.0 equiv), DCE, 70 °C, N ₂	3 ^b : yield%, dr
	2a		3aa: 93%, >20:1
	2a		3ba: 88%, >20:1
	2a		3ca: 78%, >20:1
	2a		3fa: 69%, >20:1
	2a		3ga: 83%, >20:1
	2a		3ha: 77%, 16:1
	2a		3ja: 95%, >20:1
	2a		3ka: 78%, 18:1
	2a		3la: 82%, >20:1
	2a		3ma: 61%, 14:1
	2a		3na: 80%, 13:1
	2a		3oa: 43%, 6:1
	2a		3ra: 45%, 7:1
	2a		3ap: 41%, 7:1
	2a		3ra: 49%, >20:1

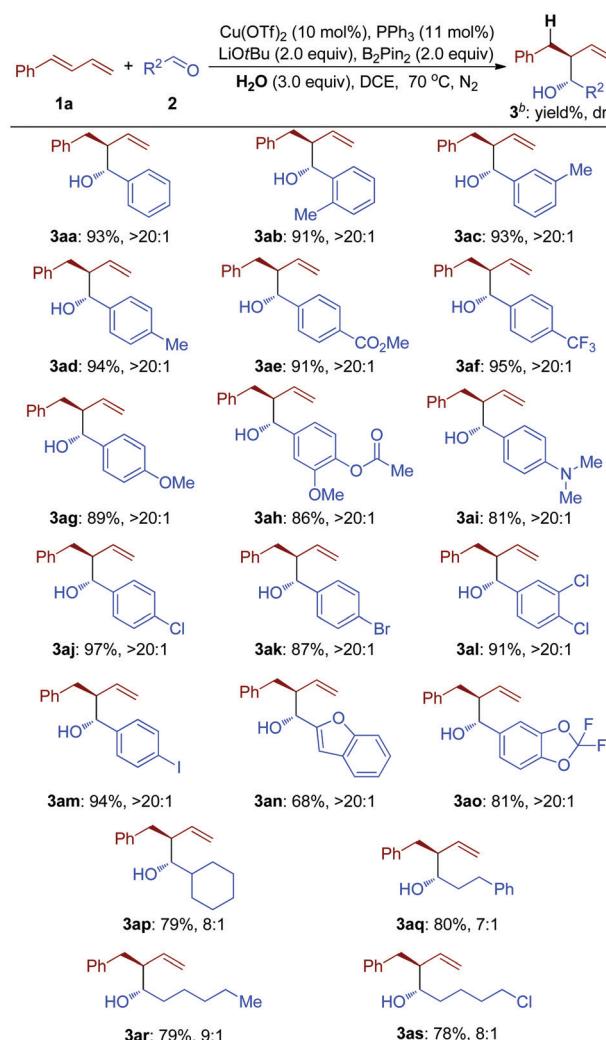
^a Standard reaction conditions: 1 (0.25 mmol), 2a (0.5 mmol), B₂Pin₂ (0.5 mmol), LiO^t-Bu (0.5 mmol), Cu(OTf)₂ (10 mol%), PPh₃ (11 mol%), H₂O (3.0 equiv.), DCE (1.5 mL), 70 °C, under N₂ condition. ^b Isolated yield, diastereomers are inseparable, dr was determined by ¹H-NMR.

when bromo-substituted or iodo-substituted arylaldehyde was employed as a starting material, good results were afforded (3ak and 3am, Table 3). These products could be used for a further coupling reaction to make complicated molecules. Moreover, under these ambient reaction conditions, the substrates with hetero-cycle groups could be converted into the desired products with good efficiency, which demonstrated the good substrate tolerance of this method (3an and 3ao, Table 3). Furthermore, the substrate scope was expanded to alkyl aldehydes, affording good yields and moderate diastereoselectivity (3ap to 3as, Table 3).

To test the feasibility of a large-scale reaction, the reaction of (*E*)-buta-1,3-dien-1-ylbenzene (1a) (11.5 mmol) and benzaldehyde (2a) (23 mmol) was investigated. The reaction afforded 2.0 g of 3aa (75% yield) with great diastereoselectivity (a, Scheme 2). The product of this chemistry, which installed a terminal alkenyl group, is a kind of versatile intermediate for chemical synthesis. As shown in Scheme 2, the product 3aa went through an epoxidation reaction,⁸ a Heck reaction,⁹ a hydroboration–oxidation reaction¹⁰ and a radical coupling reaction¹¹ to afford the desired complex products smoothly (b, c, d and e, Scheme 2).

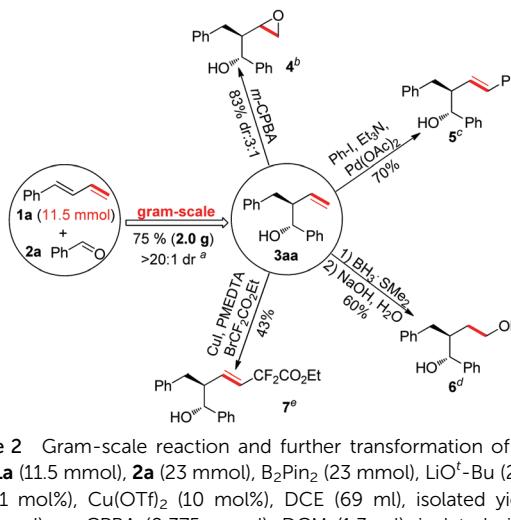
To investigate the mechanism of this transformation, control experiments were designed. Firstly, without benzaldehyde (2a), compound 8 was separated with 96% yield (eqn (1), Scheme 3).

Table 3 Cu-Catalyzed B_2Pin_2 mediated reductive reaction of **1a** with different aldehydes (**2**)^a

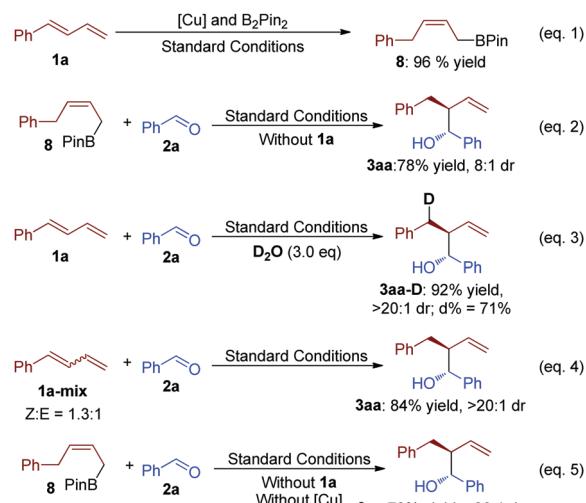


^a Standard reaction conditions: **1a** (0.25 mmol), **2** (0.5 mmol), B_2Pin_2 (0.5 mmol), $\text{LiO}^{\text{t-Bu}}$ (0.5 mmol), $\text{Cu}(\text{OTf})_2$ (10 mol%), PPh_3 (11 mol%), H_2O (3.0 equiv.), DCE (1.5 ml), 70 °C, under N_2 condition. ^b Isolated yield, diastereomers are inseparable, dr was determined by $^1\text{H-NMR}$.

This result suggested that **8** should be the key intermediate of the present transformation. Furthermore, when it was put under similar standard conditions, the desired product **3aa** was afforded with good yield (eqn (2), Scheme 3). A slight difference in the reaction system might affect the diastereoselectivity and yield, which exhibited the advantage of this one pot-reaction strategy. The reaction of **1a** and **2a** was tested in the presence of D_2O , and the D-labeled product could be detected (eqn (3), Scheme 3). This result proved that H_2O is the stoichiometric H atom donor of the Cu-catalyzed B_2Pin_2 mediated highly selective reductive transformation. Importantly, when a mixed *Z* and *E* version of buta-1,3-dien-1-ylbenzene was selected as the starting material, this chemistry afforded a similar result to the example of **3aa** from Table 1 (eqn (4), Scheme 3). This data suggests that the isomerization process of the allyl copper intermediate might be involved in this transformation. Furthermore, without



Scheme 2 Gram-scale reaction and further transformation of the product. ^a **1a** (11.5 mmol), **2a** (23 mmol), B_2Pin_2 (23 mmol), $\text{LiO}^{\text{t-Bu}}$ (23 mmol), PPh_3 (11 mol%), $\text{Cu}(\text{OTf})_2$ (10 mol%), DCE (69 ml), isolated yield. ^b **3aa** (0.25 mmol), *m*-CPBA (0.375 mmol), DCM (1.3 ml), isolated yield. ^c **3aa** (0.185 mmol), Ph-I (0.37 mmol), $\text{Pd}(\text{OAc})_2$ (10 mol%), Et_3N (1.85 mmol), CH_3CN (1.8 ml), isolated yield. ^d **3aa** (0.2 mmol), $\text{BH}_3\text{-SMe}_2$ (0.6 mmol), NaOH (0.9 mmol), H_2O_2 (1.2 mmol), THF (2.0 ml), isolated yield. ^e **3aa** (0.2 mmol), $\text{BrCF}_2\text{CO}_2\text{Et}$ (0.3 mmol), CuI (10 mol%), PMDETA (0.3 mmol), CH_3CN (1.0 ml), isolated yield.

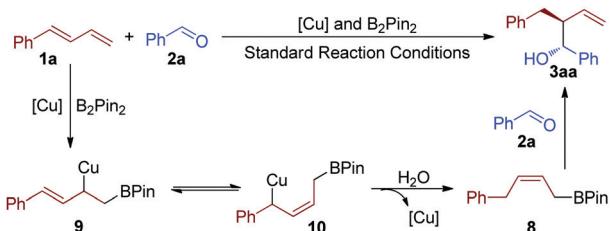


Scheme 3 Control experiments.

a copper-catalyst, **8** reacted with **2a** afforded **3aa** with good yield and diastereoselectivity (eqn (5), Scheme 3). This result suggests that copper did not participate in this step of the reaction.

On the basis of the above control experiments, a proposed mechanism for the highly selective reductive reaction is illustrated in Scheme 4. The first step of this reaction is the formation of the tautomeric copper complexes **9** and **10**.^{4c,f,12} The intermediate **10** reacted with water to give intermediate **8**, which was proved by the control experiment.^{4f} Further reaction of **8** with benzaldehyde (**2a**) afforded product **3aa**.¹³

In summary, we have demonstrated a novel Cu-catalyzed B_2Pin_2 mediated highly selective reductive functionalization of 1,3-diene using H_2O as the hydrogen donor. This practical chemistry afforded the terminal alkanyl group containing



Scheme 4 The proposed reaction mechanism.

product with various substrate scopes, a useful building block for use in organic synthesis. Furthermore, this method supported gram-scale preparation without diminished diastereoselectivity. Further studies into synthetic applications are ongoing in our laboratory.

We acknowledge financial support from Tianjin University, the National Science Foundation of China (No. 21801181), the “1000-Youth Talents Plan” and the State Key Laboratory of Elemento-Organic Chemistry (Nankai University). We acknowledge Prof. Ning Jiao (Peking University), Prof. Zhuangzhi Shi (Nanjing University) and Prof. Jun-An Ma (Tianjin University) for helpful discussions.

Conflicts of interest

The authors declare no competing financial interest.

Notes and references

- (a) *Transition Metals for Organic Synthesis, Building Block and Fine Chemicals*, ed. M. Beller and C. Bolm, Wiley-VCH, Weinheim, 2nd edn, 2004; (b) *Metal-Catalyzed Cross-Coupling Reactions*, ed. F. Diederich and A. de Meijere, Wiley-VCH, Weinheim, 2nd edn, 2004.
- For selected reviews on 1,3-dienes as building blocks in recent 10 years, see: (a) M. Büschleb, S. Dorich, S. Hanessian, D. Tao, K. B. Schenthal and L. E. Overman, *Angew. Chem., Int. Ed.*, 2016, **55**, 4156; (b) M. M. Heravi, T. Ahmadi, M. Ghavidel, B. Heidari and H. Hamidi, *RSC Adv.*, 2015, **5**, 101999; (c) J.-R. Chen, X.-Q. Hu, L.-Q. Lu and W.-J. Xiao, *Chem. Rev.*, 2015, **115**, 5301; (d) E. McNeill and T. Ritter, *Acc. Chem. Res.*, 2015, **48**, 2330; (e) Y. Zhu, R. G. Cornwall, H. Du, B. Zhao and Y. Shi, *Acc. Chem. Res.*, 2014, **47**, 3665.
- For some selected examples on 1,3-dienes as building blocks in recent 10 years, see: (a) X.-H. Yang, R. T. Davison, S.-Z. Nie, F. A. Cruz, T. M. McGinnis and V. M. Dong, *J. Am. Chem. Soc.*, 2019, **141**, 3006; (b) X.-H. Yang, R. T. Davison and V. M. Dong, *J. Am. Chem. Soc.*, 2018, **140**, 10443; (c) L. Cheng, M.-M. Li, L.-J. Xiao, J.-H. Xie and Q.-L. Zhou, *J. Am. Chem. Soc.*, 2018, **140**, 11627; (d) M.-S. Wu, T. Fan, S.-S. Chen, Z.-Y. Han and L.-Z. Gong, *Org. Lett.*, 2018, **20**, 2485; (e) X.-H. Yang and V. M. Dong, *J. Am. Chem. Soc.*, 2017, **139**, 1774; (f) J. S. Marcum, C. C. Roberts, R. S. Manan, T. N. Cervarich and S. J. Meek, *J. Am. Chem. Soc.*, 2017, **139**, 15580; (g) S.-S. Chen, M.-S. Wu and Z.-Y. Han, *Angew. Chem., Int. Ed.*, 2017, **56**, 6641; (h) Z.-L. Tao, A. Adili, H.-C. Shen, Z.-Y. Han and L.-Z. Gong, *Angew. Chem., Int. Ed.*, 2016, **55**, 4322; (i) Y. Liu, Y. Xie, H. Wang and H. Huang, *J. Am. Chem. Soc.*, 2016, **138**, 4314; (j) K. D. Nguyen, D. Herkommer and M. J. Krische, *J. Am. Chem. Soc.*, 2016, **138**, 14210; (k) C. C. Roberts, D. M. Matías, M. J. Goldfogel and S. J. Meek, *J. Am. Chem. Soc.*, 2015, **137**, 6488; (l) V. Saini, M. O'Dair and M. S. Sigman, *J. Am. Chem. Soc.*, 2015, **137**, 608; (m) X. Wu, H.-C. Lin, M.-L. Li, L.-L. Li, Z.-Y. Han and L.-Z. Gong, *J. Am. Chem. Soc.*, 2015, **137**, 13476; (n) M. J. Goldfogel, C. C. Roberts and S. J. Meek, *J. Am. Chem. Soc.*, 2014, **136**, 6227; (o) B. J. Stokes, L. Liao, A. Me de Andrade, Q. Wang and M. S. Sigman, *Org. Lett.*, 2014, **16**, 4666; (p) B. Y. Park, T. P. Montgomery, V. J. Garza and M. J. Krische, *J. Am. Chem. Soc.*, 2013, **135**, 16320; (q) L. Liao, R. Jana, K. B. Urkalan and M. S. Sigman, *J. Am. Chem. Soc.*, 2011, **133**, 5784; (r) C. H. Schuster, B. Li and J. P. Morken, *Angew. Chem., Int. Ed.*, 2011, **50**, 7906; (s) L. Liao and M. S. Sigman, *J. Am. Chem. Soc.*, 2010, **132**, 10209.
- (a) C. Li, R. Y. Liu, L. T. Jesikiewicz, Y. Yang, P. Liu and S. L. Buchwald, *J. Am. Chem. Soc.*, 2019, **141**, 5062; (b) Y. Huang, S. Torker, X. Li, J. D. Pozo and A. H. Hoveyda, *Angew. Chem., Int. Ed.*, 2019, **58**, 2685; (c) K. B. Smith, Y. Huang and M. K. Brown, *Angew. Chem., Int. Ed.*, 2018, **57**, 6146; (d) Y. Liu, D. Fiorito and C. Mazet, *Chem. Sci.*, 2018, **9**, 5284; (e) Y.-Y. Gui, N. Hu, X.-W. Chen, L.-L. Liao, T. Ju, J.-H. Ye, Z. Zhang, J. Li and D.-G. Yu, *J. Am. Chem. Soc.*, 2017, **139**, 17011; (f) S. R. Sardini and M. K. Brown, *J. Am. Chem. Soc.*, 2017, **139**, 9823; (g) T. Iwasaki, R. Shimizu, R. Imanishi, H. Kuniyoshi and N. Kambe, *Angew. Chem., Int. Ed.*, 2015, **54**, 9347.
- D. G. Hall, *Boronic Acids*, Wiley-VCH, Weinheim, 2nd edn, 2011.
- (a) K. Duvvuri, K. R. Dewese, M. M. Parsutkar, S. M. Jing, M. M. Mehta, J. C. Gallucci and T. V. RajanBabu, *J. Am. Chem. Soc.*, 2019, **141**, 7365; (b) M. E-Viguri, S. E. Neale, N. T. Coles, S. A. Macgregor and R. L. Webster, *J. Am. Chem. Soc.*, 2019, **141**, 572; (c) D. Fiorito and C. Mazet, *ACS Catal.*, 2018, **8**, 9382; (d) S. Gao, M. Wang and M. Chen, *Org. Lett.*, 2018, **20**, 7921; (e) M. Morimoto, T. Miura and M. Murakami, *Angew. Chem., Int. Ed.*, 2015, **54**, 12659; (f) R. J. Ely and J. P. Morken, *Org. Synth.*, 2011, **88**, 342; (g) R. E. Kyne, M. C. Ryan, L. T. Kliman and J. P. Morken, *Org. Lett.*, 2010, **12**, 3796; (h) R. J. Ely and J. P. Morken, *J. Am. Chem. Soc.*, 2010, **132**, 2534; (i) J. Y. Wu, B. Moreau and T. Ritter, *J. Am. Chem. Soc.*, 2009, **131**, 12915; (j) Y. Matsumoto and T. Hayashi, *Tetrahedron Lett.*, 1991, **32**, 3387.
- (a) S. P. Cummings, T.-N. Le, G. E. Fernandez, L. G. Quiambao and B. J. Stokes, *J. Am. Chem. Soc.*, 2016, **138**, 6107; (b) Y.-T. Xia, X.-T. Sun, L. Zhang, K. Luo and L. Wu, *Chem. - Eur. J.*, 2016, **22**, 17151; (c) A. G. Campaña, R. E. Estévez, N. Fuentes, R. Robles, J. M. Cuerva, E. Buñuel, D. Cárdenas and J. E. Oltra, *Org. Lett.*, 2007, **9**, 2195; (d) J. M. Cuerva, A. G. Campana, J. Justicia, A. Rosales, J. L. Oller-Lopez, R. Robles, D. J. Cardenas, E. Bunuel and J. E. Oltra, *Angew. Chem., Int. Ed.*, 2006, **45**, 5522; (e) D. A. Spiegel, K. B. Wiberg, L. N. Schacherer, M. R. Medeiros and J. L. Wood, *J. Am. Chem. Soc.*, 2005, **127**, 12513.
- 8 F. Benfatti, G. Cardillo, L. Gentilucci and A. Tolomelli, *Eur. J. Org. Chem.*, 2007, 3199.
- 9 K. L. Bolduc, S. D. Larsen and D. H. Sherman, *Chem. Commun.*, 2012, **48**, 6414.
- 10 L. Huang, Y. Cai, C. Zheng, L.-X. Dai and S.-L. You, *Angew. Chem., Int. Ed.*, 2017, **56**, 10545.
- 11 X. Wang, S. Zhao, J. Liu, D. Zhu, M. Guo, X. Tang and G. Wang, *Org. Lett.*, 2017, **19**, 4187.
- 12 (a) J. Hu, Y. Zhao and Z. Shi, *Nat. Catal.*, 2018, **1**, 860; (b) P. Gao, C. Yuan, Y. Zhao and Z. Shi, *Chem.*, 2018, **4**, 2201; (c) D. Li, Y. Park and J. Yun, *Org. Lett.*, 2018, **20**, 7526; (d) K. B. Smith and M. K. Brown, *J. Am. Chem. Soc.*, 2017, **139**(23), 7721; (e) L. Jiang, P. Cao, M. Wang, B. Chen, B. Wang and J. Liao, *Angew. Chem., Int. Ed.*, 2016, **55**, 13854; (f) K. Semba, M. Shinomiya, T. Fujihara, J. Terao and Y. Tsuji, *Chem. - Eur. J.*, 2013, **19**, 7125.
- 13 (a) T. Miura, J. Nakahashi, T. Sasatsu and M. Murakami, *Angew. Chem., Int. Ed.*, 2019, **58**, 1138; (b) H. E. Burks, L. T. Kliman and J. P. Morken, *J. Am. Chem. Soc.*, 2009, **131**, 9134; (c) L. T. Kliman, S. N. Mlynarski, G. E. Ferris and J. P. Morken, *Angew. Chem., Int. Ed.*, 2012, **51**, 521.